



University of Kentucky
UKnowledge

Theses and Dissertations--Forestry and Natural
Resources

Forestry and Natural Resources

2013

FOREST HARVEST EQUIPMENT MOVEMENT AND SEDIMENT DELIVERY TO STREAMS

Daniel Whiteside Bowker
University of Kentucky, danielwbowker@gmail.com

[Right click to open a feedback form in a new tab to let us know how this document benefits you.](#)

Recommended Citation

Bowker, Daniel Whiteside, "FOREST HARVEST EQUIPMENT MOVEMENT AND SEDIMENT DELIVERY TO STREAMS" (2013). *Theses and Dissertations--Forestry and Natural Resources*. 12.
https://uknowledge.uky.edu/forestry_etds/12

This Master's Thesis is brought to you for free and open access by the Forestry and Natural Resources at UKnowledge. It has been accepted for inclusion in Theses and Dissertations--Forestry and Natural Resources by an authorized administrator of UKnowledge. For more information, please contact UKnowledge@lsv.uky.edu.

STUDENT AGREEMENT:

I represent that my thesis or dissertation and abstract are my original work. Proper attribution has been given to all outside sources. I understand that I am solely responsible for obtaining any needed copyright permissions. I have obtained and attached hereto needed written permission statements(s) from the owner(s) of each third-party copyrighted matter to be included in my work, allowing electronic distribution (if such use is not permitted by the fair use doctrine).

I hereby grant to The University of Kentucky and its agents the non-exclusive license to archive and make accessible my work in whole or in part in all forms of media, now or hereafter known. I agree that the document mentioned above may be made available immediately for worldwide access unless a preapproved embargo applies.

I retain all other ownership rights to the copyright of my work. I also retain the right to use in future works (such as articles or books) all or part of my work. I understand that I am free to register the copyright to my work.

REVIEW, APPROVAL AND ACCEPTANCE

The document mentioned above has been reviewed and accepted by the student's advisor, on behalf of the advisory committee, and by the Director of Graduate Studies (DGS), on behalf of the program; we verify that this is the final, approved version of the student's dissertation including all changes required by the advisory committee. The undersigned agree to abide by the statements above.

Daniel Whiteside Bowker, Student

Dr. Jeffrey Stringer, Major Professor

Dr. David Wagner, Director of Graduate Studies

FOREST HARVEST EQUIPMENT MOVEMENT AND SEDIMENT DELIVERY TO
STREAMS

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in the
College of Agriculture
at the University of Kentucky

By

Daniel Whiteside Bowker

Lexington, Kentucky

Director: Dr. Jeffrey W. Stringer, Extension Professor of Hardwood Silviculture and
Forest Operations

Lexington, Kentucky

2013

Copyright © Daniel Whiteside Bowker 2013

ABSTRACT OF THESIS

FOREST HARVEST EQUIPMENT MOVEMENT AND SEDIMENT DELIVERY TO STREAMS

Streamside management zones (SMZs) have become important management techniques to prevent the introduction of sediment to stream networks. This study examined the current Kentucky best management practice (BMP) guidelines for SMZs by outfitting mobile forest harvest equipment with global positioning system (GPS) receivers, enabling modeling of equipment traffic and spatial analysis of stream sediment delivery. Three SMZ configurations were implemented during commercial timber harvest, along with four different techniques of crossing ephemeral channels, in order to determine where and why sediment was introduced to the stream network. Results indicate that increasing the SMZ buffer width leads to decreased sediment delivery, and that requiring an SMZ buffer with some canopy retention on ephemeral channels will lead to improvements in stream water quality. Care should be taken in the placement and construction of water control measures for skid trail retirement, and improved stream channel crossings such as bridges and pipe culverts should be required to improve water quality over unimproved fords. A northeasterly aspect of harvested areas was shown to be related to increased sediment delivery to streams, while surface roughness downslope from the skid trail system was shown to decrease sediment delivery.

KEYWORDS: streamside management zone, sediment path, forest harvest, GPS, stream crossings

Daniel Bowker

April 29, 2013

FOREST HARVEST EQUIPMENT MOVEMENT AND SEDIMENT DELIVERY TO
STREAMS

By

Daniel Whiteside Bowker

Dr. Jeffrey Stringer

Director of Thesis

Dr. David Wagner

Director of Graduate Studies

April 29, 2013

This work is dedicated to my wife Cheryl, without whose inspiration, encouragement, persistence, and devotion I would not make it through another day, much less another degree.

ACKNOWLEDGEMENTS

The following thesis, while an individual work, has benefitted greatly from the insights, knowledge, and friendship of my advisor Dr. Jeff Stringer, as well as the members of my committee, Dr. Chris Barton and Dr. Marco Contreras. My parents, Bill and Linda Bowker, remain endlessly supportive of all my endeavors. Scott Baggett at the Rocky Mountain Research Station provided much needed statistical help. Chris Reeves, Dr. Emma Witt, and Aaron Klee deserve special thanks for the many hours of tireless work they put in on the project itself, never unwilling to lend a hand. Chris Osborne and Courtney Mastin put their backs into it as well, and the mountain of data collected would not have been possible without the efforts of Clint Lester, Nik Eiche, Jon Watts, Megan Buland, Matt Strong, Craig Blocker, Ellery Watson, and Sarah Shewmaker. The Robinson Forest crew of David Collett and Ted Sizemore was invaluable, always available, usually with a piece of heavy machinery, to get things put into place. My old dog Hal wandered miles of skid trails with me for the price of a scratch behind the ears. Finally, my friend Will Marshall provided the kind of quiet leadership and gentle support that can never be repaid. May his soul lightly roam that Clemons Fork hollow, and may his troubles be lifted forever.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vi
LIST OF FIGURES	ix
CHAPTER I: INTRODUCTION.....	1
I.1. Best management practices: Streamside management zones and stream crossings	2
I.2. BMP research and need for present study	5
I.3. Study overview	7
CHAPTER II: OVERLAND SEDIMENT DELIVERY STUDY	10
II.1. Introduction	10
II.2. Methods.....	11
II.2.i. Study area.....	11
II.2.ii. Streamside management zone project and harvest operations	13
II.2.iii. Field surveys, GPS tracking of harvest, GIS analysis	15
II.2.iv. Data analysis	26
II.3. Results and discussion.....	28
II.3.i. Performance of MultiDAT GPS dataloggers during harvest operations.....	28
II.3.ii. Machine-caused overland sediment delivery pathways	30
II.3.ii.a. General characteristics of machine-caused sediment paths	30
II.3.ii.b. Water control structure influence on sediment paths.....	32
II.3.ii.c. Comparison of machine-caused sediment paths by treatment	37
II.3.ii.d. Modeling of significant factors in machine-caused sediment path development.....	40
II.3.iii. Undisturbed forest floor overland sediment delivery pathways	47
II.3.iii.a. General characteristics of undisturbed sediment paths	47
II.3.iii.b. Comparison of undisturbed sediment paths by treatment.....	49
II.3.iii.c. Modeling of significant factors in undisturbed sediment path development.....	52
II.3.iv. Combined machine-caused and undisturbed overland sediment delivery pathways	60
II.3.iv.a. General characteristics of combined machine-caused and undisturbed sediment paths.....	60
II.3.iv.b. Comparison of combined machine-caused and undisturbed sediment paths by treatment	62

II.3.iv.c. Modeling of significant factors in combined machine-caused and undisturbed sediment path development.....	65
II.3.v. Relationship between machine-caused and undisturbed overland sediment delivery pathways	69
II.4. Summary of sediment path study	71
CHAPTER III: STREAM CROSSING STUDY	128
III.1. Introduction.....	128
III.2. Methods	130
III.2.i. Study area	130
III.2.ii. Streamside management zone project and harvest operations.....	130
III.2.iii. Four types of stream crossings	130
III.2.iv. Water sampling procedures	135
III.2.v. GPS tracking and GIS analysis	136
III.2.vi. Time study of stream crossing options	140
III.2.vii. Data analysis	140
III.3. Results and discussion	141
III.3.i. Performance of MultiDAT GPS dataloggers during harvest operations	141
III.3.ii. Summary of effects of improved crossings and treatments on differences in total suspended solids (TSS) and turbidity from Witt et al. (2013)	142
III.3.iii. Environmental and operational factors correlated with turbidity levels in controls.....	144
III.3.iv. Environmental and operational factors correlated with turbidity levels in treatments	146
III.3.iv. Time study of installation, removal, and retirement of improved stream crossings.....	152
III.4. Summary of stream crossing study	155
CHAPTER IV: SUMMARY AND MANAGEMENT IMPLICATIONS	186
IV.1. SMZ buffer width and canopy retention.....	186
IV.2. Skid trail system and forest harvest equipment traffic	187
IV.3. Stream crossings	188
IV.4 Environmental factors.....	189
REFERENCES	191
VITA	196

LIST OF TABLES

Table 2.1—Treatments used for Robinson Forest Streamside Management Zone project.	77
Table 2.2—Summary table of the Robinson Forest Streamside Management Zone Project.	78
Table 2.2 continued—Summary table of the Robinson Forest Streamside Management Zone Project.	79
Table 2.3—Categories used to document observed skid trail traffic intensity (after Michels 2009).	80
Table 2.4—Categories used to document woody debris on the ground surface, with the value given to each.	81
Table 2.5—Number and type of analysis units in each of the harvest and control watersheds.	82
Table 2.6—Actual number of sediment paths documented in each treatment watershed, by stream type at which the paths terminated.	83
Table 2.7—Water control structures documented within analysis units of the three harvested watersheds, by the morphology of the skid trail where they were constructed.	84
Table 2.8.—Mean number and mean total width of machine-caused sediment paths per 1,000 ft of stream, by treatment and stream type.	85
Table 2.9—Mean coarse surface roughness values by treatment and stream type.	86
Table 2.10—Results of pairwise multivariate analyses among independent variables used for modeling.	87
Table 2.11—Summary table of linear models for harvested watersheds, using number and total width of machine-caused sediment paths per 1,000 ft of stream as the response variables, with combined traffic area index and total surface roughness.	88
Table 2.12—Summary table of linear models for harvested watersheds, using number and total width of machine-caused sediment paths per 1,000 ft of stream as the response variables, with individual machine type traffic area indices and total surface roughness.	89
Table 2.13—Summary table of linear models for harvested watersheds, using number and total width of machine-caused sediment paths per 1,000 ft of stream as the response variables, with combined traffic area index and individual types of surface roughness.	90
Table 2.14—Summary table of linear models for harvested watersheds, using number and total width of machine-caused sediment paths per 1,000 ft of stream as the response variables, with individual traffic area index and individual types of surface roughness.	91
Table 2.15—Mean number and mean total width of undisturbed sediment paths per 1,000 ft of stream, by control watershed and stream type.	92
Table 2.16—Mean number and mean total width of undisturbed sediment paths per 1,000 ft of stream, by treatment and stream type.	93
Table 2.17—Summary table of linear models for control watersheds only, using number and total width of undisturbed sediment paths per 1,000 ft of stream as the response variables, with individual types of surface roughness.	94
Table 2.18—Summary table of linear models for Falling Rock control watershed only, using number and total width of undisturbed sediment paths per 1,000 ft of stream as the response variables.	95

Table 2.19—Summary table of linear models for Little Millseat control watershed only, using number and total width of undisturbed sediment paths per 1,000 ft of stream as the response variables.	96
Table 2.20—Summary table of linear models for harvested watersheds, using number and total width of undisturbed sediment paths per 1,000 ft of stream as the response variables, with combined traffic area index and total surface roughness.....	97
Table 2.21—Summary table of linear models for harvested watersheds, using number and total width of undisturbed sediment paths per 1,000 ft of stream as the response variables, with combined traffic area index and individual surface roughness.....	98
Table 2.22—Summary table of linear models for harvested watersheds, using number and total width of undisturbed sediment paths per 1,000 ft of stream as the response variables, with individual machine type traffic area indices and total surface roughness.	99
Table 2.23—Summary table of linear models for harvested watersheds, using number and total width of undisturbed sediment paths per 1,000 ft of stream as the response variables, with individual machine type traffic area indices and individual surface roughness.	100
Table 2.24—Mean number and mean total width of combined machine-caused and undisturbed sediment paths per 1,000 ft of stream, by treatment and stream type.....	101
Table 2.25—Summary table of linear models for harvested watersheds, using number and total width of combined machine-caused and undisturbed sediment paths per 1,000 ft of stream as the response variables, with combined traffic area index and total surface roughness.	102
Table 2.26—Summary table of linear models for harvested watersheds, using number and total width of combined machine-caused and undisturbed sediment paths per 1,000 ft of stream as the response variables, with combined traffic area index and individual surface roughness.	103
Table 2.27—Summary table of linear models for harvested watersheds, using number and total width of combined machine-caused and undisturbed sediment paths per 1,000 ft of stream as the response variables, with individual machine type traffic area indices and total surface roughness.....	104
Table 2.28—Summary table of linear models for harvested watersheds, using number and total width of combined machine-caused and undisturbed sediment paths per 1,000 ft of stream as the response variables, with individual machine type traffic area indices and individual surface roughness.....	105
Table 2.29—Mean number and mean total width of machine-caused and undisturbed sediment paths per 1,000 ft of stream by stream type, harvested watersheds only.	106
Table 3.1—Stream crossings involved in this study, with type of crossing and number of traverses by harvest machine type.	161
Table 3.2—Results of pairwise multivariate analyses among independent variables used for modeling.....	162
Table 3.3—Summary table of linear regressions for the controls, using log-transformed mean turbidity as the response variable.	163
Table 3.4—Summary table of environmental, harvest operations, and stream crossing morphology linear models for the harvested units, using log-transformed mean turbidity as the response variable.	164

Table 3.5—Summary table of harvest machine traverses linear model for the harvested units, using log-transformed mean turbidity as the response variable, for all crossing types other than bridges.	165
Table 3.6—Approximate average stream crossing installation, removal, and retirement times.....	166

LIST OF FIGURES

Figure 2.1—Map showing the location of Robinson Forest within Kentucky.	107
Figure 2.2—Map showing the location of the SMZ project treatments.	108
Figure 2.3—Map of the 55ft-100% treatment watershed in green, showing units subjected to experimental analysis in orange.	109
Figure 2.4—Map of an analysis unit in the 55ft-100% treatment watershed.	110
Figure 2.5—Map of 9 analysis units (3 ephemeral, 3 intermittent, 3 perennial) in the 55ft-50% treatment watershed North Shelly Rock.	111
Figure 2.6—Map of 24 analysis units (10 ephemeral, 10 intermittent, 4 perennial) in the 110ft-100% treatment watershed West Shelly Rock.	112
Figure 2.7—Map of 11 analysis units (3 ephemeral, 4 intermittent, 4 perennial) in the 55ft-100% treatment watershed South Shelly Rock.	113
Figure 2.8—Map of 13 analysis units (3 ephemeral, 6 intermittent, 4 perennial) in control watershed Little Millseat.	114
Figure 2.9—Map of 20 analysis units (10 ephemeral, 6 intermittent, 4 perennial) in control watershed Falling Rock.	115
Figure 2.10—Map showing alignment of MultiDAT-captured harvest equipment GPS locations with GeoXM-captured skid trails in the lower section of the 55ft-100% treatment watershed.	116
Figure 2.11—Raster map showing relative traffic intensity for all harvest machines on the three study watersheds.	117
Figure 2.12—Raster map showing relative skidder traffic intensity on the three study watersheds.	118
Figure 2.13—Raster map showing relative bulldozer traffic intensity on the three study watersheds.	119
Figure 2.14—Raster map showing relative feller-buncher traffic intensity on the three study watersheds.	120
Figure 2.15—Linear regression of machine-caused sediment path distance from source to stream by degree of slope for each path, harvested watersheds only.	121
Figure 2.16—Chart showing point of origin of 72 machine-caused sediment paths.	122
Figure 2.17—Histogram of frequency of machine-caused sediment paths by degree of slope of skid trail section from which the paths originated, harvested watersheds only.	123
Figure 2.18—Linear regression of undisturbed sediment path distance from source to stream by degree of slope for each path, harvested and control watersheds.	124
Figure 2.19—Linear regression of combined sediment path distance from source to stream by degree of slope for each path, harvested and control watersheds.	125
Figure 2.20—Linear regression of number of machine-caused sediment paths per 1,000 ft of stream by number of undisturbed sediment paths per 1,000 ft of stream, harvested watersheds only.	126
Figure 2.21—Linear regression of total width of machine-caused sediment paths per 1,000 ft of stream by total width of undisturbed sediment paths per 1,000 ft of stream, harvested watersheds only.	127
Figure 3.1—A retired ford in Shelly Rock North (the 55ft-50% treatment).	167
Figure 3.2—A culvert installed in a stream channel.	168
Figure 3.3—Stream crossed by a steel pipe after retirement.	169

Figure 3.4—Completed cant panel of a portable skidder bridge.	170
Figure 3.5—Installed portable skidder bridge.	171
Figure 3.6—Retired skidder bridge crossing.	172
Figure 3.7—Drilling of PVC pipe for threading with steel cable.	173
Figure 3.8—Pipe bundle installed in a stream channel, covered with geotextile.	174
Figure 3.9—Stream channel crossed by installation of a PVC pipe bundle, after retirement.	175
Figure 3.10—Map of the 55ft-100% treatment watershed in green, showing units subjected to experimental analysis in hatched orange.	176
Figure 3.11—Map of an analysis unit in the 55ft-100% treatment watershed.	177
Figure 3.12—Screen shot from Google SketchUp showing a stream crossing in the 55ft-50% treatment as an example of the triangular prism created to model each stream crossing, in order to calculate approximate fill volume and erosional surface area after crossing retirement.	178
Figure 3.13—Map of 3 analysis units for the 55ft-50% treatment watershed North Shelly Rock.	179
Figure 3.14—Map of 4 analysis units for the 110ft-100% treatment watershed West Shelly Rock.	180
Figure 3.15—Map of 3 analysis units for the 55ft-100% treatment watershed South Shelly Rock.	181
Figure 3.16—Map of 2 analysis units for control watershed Little Millseat.	182
Figure 3.17—Map of 2 analysis units for control watershed Falling Rock.	183
Figure 3.18—Map of 2 stream crossings for the 110ft-100% treatment watershed Wet Fork.	184
Figure 3.19—Example map showing line shapefile output of GPS data of harvest equipment traversing a stream crossing location.	185

CHAPTER I: INTRODUCTION

The potential negative effects of forest management, including timber harvesting, on streams and riparian habitat are well-documented. Forest operations in and around riparian areas can cause increased nutrient delivery to streams, as well as increases in water temperature and stream sediment levels (Corbett, Lynch et al. 1978; Kochenderfer and Edwards 1990; Binkley and Brown 1993; Arthur, Coltharp et al. 1998; LeDoux and Wilkerson 2006; Rashin, Clishe et al. 2006). Elevated nutrient levels can cause eutrophication, increasing biological activity and reducing the amount of dissolved oxygen available for aquatic life, while the export of nutrients from harvested areas can decrease long-term site productivity (Corbett, Lynch et al. 1978). Increased stream temperature can also reduce the amount of oxygen available for aquatic life (Corbett, Lynch et al. 1978). Sediment can suffocate fish and aquatic invertebrates, and when deposited on the streambed can reduce or degrade spawning habitat (Corbett, Lynch et al. 1978; Binkley and Brown 1993). In the process, increased stream sedimentation can cause a reduction in the biodiversity and biomass in aquatic systems (Summer, Rhett Jackson et al. 2006). Increased sediment concentration degrades the quality of drinking water, as well as enhances the transport of sorbed pollutants, so that it costs more to properly treat water for human use (Binkley and Brown 1993; Karwan, Gravelle et al. 2007).

In 1972, the Federal Water Pollution Control Act and its related amendments directed the states to develop best management practices (BMPs) to address these non-point source pollution (NPSP) impacts of forest operations. Of the various NPS pollutants, sediment is

commonly seen as the most important type in forested areas (Miller and Everett 1975; Binkley and Brown 1993; Kreutzweiser and Capell 2001; Croke and Hairsine 2006; Summer, Rhett Jackson et al. 2006; Lakel, Aust et al. 2010).

I.1. Best management practices: Streamside management zones and stream crossings

Most sediment delivered to streams during forest operations involves road, trail, and landing construction and use (Trimble and Sartz 1957; Corbett, Lynch et al. 1978; Swift 1988; Kochenderfer and Edwards 1990; Stuart and Carr 1991; Grayson, Haydon et al. 1993; Martin and Hornbeck 1994; Kochenderfer, Edwards et al. 1997; Arthur, Coltharp et al. 1998; Ketcheson, Megahan et al. 1999; Kreutzweiser and Capell 2001; Swank, Vose et al. 2001; Hairsine, Croke et al. 2002; Aust and Blinn 2004; Benda, Hassan et al. 2005; Germain and Munsell 2005; Croke and Hairsine 2006; Rashin, Clishe et al. 2006; Stuart and Edwards 2006). In order to minimize the connectivity of the forest transportation network to the stream system, the BMPs most states created include streamside management zone (SMZ) recommendations or regulations. The SMZ is a buffer strip left undisturbed or minimally disturbed between the transportation network and the stream system, which is intended to filter flows of sediment and nutrients from the road and trail system, as well as reduce the effect of canopy removal on stream temperature (Stringer, Lowe et al. 1998; Stringer and Thompson 2000; Blinn and Kilgore 2001; Stringer and Perkins 2001). Many states' SMZ regulations attempt to mitigate the effects of the transportation network by requiring roads, trails, and landings to be located outside the SMZ (Stringer and Thompson 2000; Blinn and Kilgore 2001). SMZs have

been shown to be generally effective at reducing nutrient inputs, temperature increases, and sediment levels (Trimble and Sartz 1957; Corbett, Lynch et al. 1978; Kochenderfer and Edwards 1990; Binkley and Brown 1993; Grayson, Haydon et al. 1993; Martin and Hornbeck 1994; Kochenderfer, Edwards et al. 1997; Arthur, Coltharp et al. 1998; Wynn, Mostaghimi et al. 2000; Aust and Blinn 2004; Lakel, Aust et al. 2006; LeDoux and Wilkerson 2006; Rashin, Clishe et al. 2006; Summer, Rhett Jackson et al. 2006). However, the implementation of SMZs has an economic cost, as well as ecological benefits. The timber left unharvested in the SMZs, as well as the increased cost of navigating machines around rather than through the SMZs, can reduce net revenues significantly (Ellefson and Miles 1985; Dickinson 1992; Wang, Long et al. 2004; LeDoux and Wilkerson 2006; Richardson and Danehy 2007).

One of the main targets of streamside management regulations are overland sediment pathways, a primary mechanism by which sediment from the road and trail network can reach streams (Corner, Bassman et al. 1996). These sediment paths can bypass the vegetative filtering of the SMZ (Croke and Hairsine 2006), overwhelming the SMZ with a channelized flow of sediment-laden water and delivering this to the stream (May 2007; Lakel, Aust et al. 2010). Though this delivery mechanism is highly important in stream sedimentation during forest management, there is little direct information about these sediment delivery pathways (Croke and Hairsine 2006; Litschert and MacDonald 2009).

The other major sediment delivery mechanism during forest management, and a focus of BMP regulation, is the crossing of stream sections by the road and trail network (Taylor,

Rummer et al. 1999). Though the entire road and trail system can be at fault for sediment production and its delivery to the stream network, crossings over defined channels are the most critical points in this system (Swift 1988). At these intersections between the forest road system and the stream network, the sediment source of the unsealed road network has a short pathway to the stream, so that there is less infiltration, trapping, or diversion of runoff containing concentrated sediment (Lane and Sheridan 2002).

In Kentucky, where the present studies took place, BMP regulations address these two primary sediment delivery mechanisms with the use of SMZs and by regulating stream crossings, with the SMZ regulations varying by stream type. Kentucky's BMP regulations define ephemeral channels as those that have flowing water primarily during or directly after precipitation events or during snowmelt (Stringer and Perkins 2001). Intermittent streams are those that flow mainly during the wet season, while perennial streams typically flow year-round, except during extreme droughts (Fritz, Johnson et al. 2008; Witt, Barton et al. 2013). Kentucky mandated SMZ use on all commercial logging operations that impact perennial and intermittent streams with the passage of the 1998 Kentucky Forest Conservation Act. According to the act, SMZs on perennial streams must be 25 ft wide on ground sloping less than 15% from the streambank, and 55 ft wide on ground sloping more than 15% from the streambank; no roads, trails, landings, or harvest machine use should occur in this zone, and 50% of the canopy trees must be retained (Stringer, Lowe et al. 1998; Stringer and Perkins 2001). For Kentucky intermittent streams, a 25 ft buffer excluding roads, trails, landings, and harvest machine use is required regardless of slope; all trees may be removed from this buffer (Stringer,

Lowe et al. 1998; Stringer and Perkins 2001). Ephemeral streams in Kentucky receive no SMZ buffer zone protection for transportation network location, equipment operation, or canopy retention (Stringer, Lowe et al. 1998; Stringer and Perkins 2001). For all stream types, stream crossings should be avoided if possible; where crossing a stream is unavoidable, the crossing should be made at right angles, and the use of an improved or elevated crossing (such as a culvert or temporary bridge) is preferred, though not required by the law (Stringer and Perkins 2001).

I.2. BMP research and need for present study

Many states' SMZ regulations or recommendations stem from research done in the White Mountains of New Hampshire in the 1950's, with regional variations based upon differences in geology, soils, and harvesting systems (Trimble and Sartz 1957). However, little research has been done to tailor these recommendations to specific regions or sites, and very few studies have looked into the efficacy of different buffer widths and canopy retention levels (Corner, Bassman et al. 1996; Arthur, Coltharp et al. 1998; Blinn and Kilgore 2001; Aust and Blinn 2004; Lakel, Aust et al. 2006; Rashin, Clishe et al. 2006; Edwards and Williard 2010; Lakel, Aust et al. 2010). In fact, the lack of region and site specific information about SMZ buffers is partly responsible for the wide variations in SMZ regulations and recommendations among states (Stringer and Thompson 2000). Most research that has been done on BMPs and SMZs has been directed at larger order streams; smaller order, or headwater, streams are more difficult to access and study, and have less fish habitat (Benda, Hassan et al. 2005; Rashin, Clishe et al. 2006). Headwater streams, though largely ignored from a regulatory perspective (MacDonald and Coe

2007), can comprise 60-80% of the drainage network, and headwater stream impacts during forest operations have much to do with providing sediment and wood to larger streams (Benda, Hassan et al. 2005; May 2007). There is a need for research into the mechanisms delivering sediment to small streams (Arthur, Coltharp et al. 1998; Aust and Blinn 2004; MacDonald and Coe 2007), and specifically how forest harvesting machinery and its associated transportation network deliver this sediment (Kreutzweiser and Capell 2001). This study attempts to uncover the processes by which sediment gets delivered to the stream system within the watershed, and not merely at the cumulative effect of timber harvesting on water quality at the watershed outlet.

Research into BMP effectiveness has been called an example of an “iterative adaptive management process,” in which BMPs are established with the best available information, the effectiveness of BMP implementation is monitored, and the BMPs are then improved based upon this information (Rashin, Clishe et al. 2006). As the adoption of BMPs, whether voluntary or mandatory, has spread in the United States, research into the implementation of these BMPs in different forest settings has only recently been undertaken, with much left to investigate. Once reliable experimental data is gathered for specific regions and sites, BMPs can be refined for those particular areas.

Research detailing the impacts of Kentucky’s current BMP regulations is needed. As a major hardwood timber producer, Kentucky’s forests continue to see harvesting and forest management pressure, while the health of Kentucky’s waterways remains a concern. Since Kentucky’s Forest Conservation Act took effect, BMP implementation

has been monitored by the Kentucky Division of Forestry and the University of Kentucky Department of Forestry. Monitoring results have been encouraging; however, refinement of the BMP regulations for site specific conditions is now needed. Research is needed into protecting riparian function using SMZs and stream crossings, while still allowing the timber operator to conduct the harvest profitably (Miller and Everett 1975). If the current regulations are not protecting the ecological integrity of Kentucky's waterways, they need to be strengthened to do so. However, if the current regulations are sufficiently protecting Kentucky's water quality, they should not be unnecessarily tightened, so that timber operators and the forest products industry can continue to thrive in the Commonwealth.

I.3. Study overview

The overall study objective was to determine relationships between harvesting equipment positioning and movement relative to suspended sediment production. The study was conducted in eastern Kentucky in highly dissected and steep topography. Specifically we monitored the movements of road building and harvesting machines on a commercial timber harvest, while detailing the effects of the road building and harvesting activity on stream sediment levels and delivery mechanisms. All mobile harvest machines were fitted with global positioning system (GPS) receivers and positional data was gathered during the harvest operation. Analyzing this data in a geographic information system (GIS), allowed modeling the relationships among machine movements, production of disturbed ground, overland sediment delivery paths, and different types of stream crossings. In particular, the intensity of forest harvest machine traffic in areas near SMZs

was quantified in order to determine if traffic intensity, along with several other environmental variables, had an effect on the number and relative magnitude of overland sediment flows into and through the SMZ. Three configurations of SMZ buffer width and canopy retention and associated equipment traffic intensities within SMZs were studied to determine effects on overland sediment delivery to streams. Further, we tested four different types of stream crossings (unimproved fords, steel pipes, pipe mat bundles, and portable skidder bridges) to determine if there were differences in their potential for sediment delivery to streams during installation, use, and removal. The GPS data allowed analysis of the number of machine traverses over these stream crossings and the cumulative effect of crossing type and machine traverses on sediment delivery to streams (details in Methods sections).

GPS tracking of forest machine movements has been shown to be effective in obtaining detailed information on harvest machine use of the forest transportation network and how this use is related to environmental variables (Carter, McDonald et al. 1999; Taylor, McDonald et al. 2001; Veal, Taylor et al. 2001; McDonald, Carter et al. 2002; Davis and Kellogg 2005; Michels 2009). GPS accuracies under heavy forest canopy can cause some reliability problems with the data (Deckert and Bolstad 1996); however, data reliability is sufficient to produce workable maps of harvest machine traffic patterns (Carter, McDonald et al. 1999; Veal, Taylor et al. 2001; McDonald, Carter et al. 2002). The positional information gathered can produce maps showing areas of different traffic intensities (Carter, McDonald et al. 1999; Taylor, McDonald et al. 2001; Veal, Taylor et al. 2001; McDonald, Carter et al. 2002; Davis and Kellogg 2005; Michels 2009). These

maps can be analyzed with sediment delivery data to show how different traffic intensities and control points such as stream crossings contribute to the sedimentation of harvest area streams. This information should lead to better transportation network planning and design and provide information beneficial for testing the effectiveness of current BMP regulations as well as provide alternatives to further reduce potential sediment delivery to streams.

CHAPTER II: OVERLAND SEDIMENT DELIVERY STUDY

II.1. Introduction

Overland sediment pathways are one of the primary means by which sediment-laden runoff enters the stream network during forest management (Corner, Bassman et al. 1996). Rivenbark and Jackson (2004) discovered that overland sediment flows generated from forest management activities were capable of spanning the SMZ and delivering sediment to streams, and were highly variable among sites, though the sites had similar topography, soils, and silvicultural treatments. Fifty percent of these breakthroughs occurred in areas of convergent topography (where downhill flows of water come together), while 25% were caused by drainage from the road and trail system (Rivenbark and Jackson 2004). Ward and Jackson (2004) found that SMZs had an ameliorating effect on reducing sediment transport following forest harvest, reducing sediment by 71 to 99 percent; however, no statistical model accurately explained the variation in SMZ efficiency. A sediment routing survey by Rashin et al. (2006) showed that ground disturbance within 10 meters of a stream was likely to deliver sediment to the stream. White et al. (2007) found that a narrow SMZ effectively removed coarse textured ($>20\text{ }\mu\text{m}$) sediments from concentrated overland flows of runoff water, while a wider 16 meter SMZ removed the majority of 2 to $20\text{ }\mu\text{m}$ sediments. Litschert and MacDonald (2009) found that the length of sediment delivery pathways in the Sierra Nevada and Cascade Mountains of California were significantly related to mean annual precipitation, the cosine of the aspect, elevation, and hillslope gradient. Eighty-three percent of these pathways that they found actually connected to the stream network originated from a skid trail (Litschert and MacDonald 2009). A study in the Virginia Piedmont testing the

efficacy of three different SMZ buffer widths by Lakel et al. (2010) found that wider SMZ buffers were no more effective than narrower buffers in preventing overland sediment flows from reaching streams, and the sediment pathways found passed through the SMZ regardless of width. In all cases these flows were caused by failed water control structures on steep slopes with fragile soils.

While these studies are useful in understanding the factors contributing to the production of overland sediment delivery pathways during forest management, none of them were conducted at sites with the unique topography of the Cumberland Plateau, and none used GPS positional data to understand the relationship of machine traffic patterns to production of sediment flows. The specific objectives of this study were to:

- integrate machine traffic pattern data into an analysis of sediment flow pathway initiation,
- investigate the site factors contributing to this initiation in the steeply sloping ground of the Cumberland Plateau in eastern Kentucky, and
- provide information on the effectiveness of current BMP requirements and alternatives to further reduce sediment delivery.

II.2. Methods

II.2.i. Study area

The study took place June 2008 through October 2009 on the University of Kentucky's Robinson Forest, a 15,000 acre experimental forest located in Breathitt, Knott, and Perry Counties in eastern Kentucky (figure 2.1). The forest is in the rugged eastern area of the

Cumberland Plateau (longitude -83.14° W, latitude 37.47° N), and is composed of mixed mesophytic and oak-hickory forest types (Overstreet 1984). The forest was selectively harvested prior to 1900 and intensively harvested from 1908-1923 by the Mowbray and Robinson Lumber Company, and has since grown into an 80-100 year old even-aged forest.

This section of the Cumberland Plateau is characterized by deep valleys, steep valley walls, and long narrow ridges; elevations in Robinson Forest range from 800 to 1600 ft above mean sea level (Overstreet 1984). Geology consists of interbedded sandstone, siltstone, shale, and coal, while soils in the study area classified into three main groups: the Cloverlick-Shelocta-Cutshin complex, the Dekalb-Marrowbone-Latham complex, and the Shelocta-Gilpin-Hazleton complex (U.S. Department of Agriculture Natural Resources Conservation Service 2009). The Cloverlick-Shelocta-Cutshin complex is a deep, well-drained silt loam found on shaded slopes; the Dekalb-Marrowbone-Latham complex is shallow to moderately deep, well-drained, rocky or stony, silty clay to loam on the upper third of steep hillsides; and the Shelocta-Gilpin-Hazleton complex is a shallow to moderately deep, well-drained, rocky or stony, silty clay to loam associated with warm side slopes (U.S. Department of Agriculture Natural Resources Conservation Service 2009). All three soil complexes in the study area are classified as severely erodible both on and off roads and trails, and as poorly suited for roads (U.S. Department of Agriculture Natural Resources Conservation Service 2009). Owing to their similarity relative to erodibility and road construction, the three soil complexes comprising the study area will be treated as essentially similar for the purpose of this study.

The area of eastern Kentucky in which Robinson Forest lies has a mean annual temperature of 56.6° F, and receives an average of 48.3 inches of precipitation each year, the majority of which falls as rain (National Weather Service 2012). Precipitation is not distributed uniformly throughout the year or within seasons. Typically droughty summers with wet seasons and storms play a significant part in the delivery of annual precipitation. The Cumberland Plateau's topography is due mainly to the erosional forces of this annual precipitation; a 24 hour storm event on May 8 and 9, 2009, produced 2.83 inches of rain (National Weather Service 2012) and was a major factor in the results of the two analyses detailed here.

The study took place in the northern portion of the main tract of Robinson Forest (figure 2.2) within the Clemons Fork watershed. The Clemons Fork watershed is designated for hydrological research by the Robinson Forest Technical Committee, which is responsible for determining acceptable use of the forest land base. The study subwatersheds comprised approximately 1,253 acres of the 10,010 acre total area of the main tract of Robinson Forest. Approximately 820 acres of those 1,253 acres were harvested during the study, with 433 acres used as unharvested controls.

II.2.ii. Streamside management zone project and harvest operations

The studies detailed in this thesis form part of a larger research undertaking concerning the effects of timber harvesting on headwater stream quality. The Robinson Forest Streamside Management Zone project (SMZ project), is a paired watershed study with replications (Brooks, Ffolliott et al. 2003), intended to investigate the water quality

effects on headwater stream systems with varying configurations of SMZ buffer widths and canopy retention levels.

Operationally, the SMZ project involved commercial timber harvest on 6 forested watersheds, with 2 unharvested controls. The 6 watersheds comprised 2 replications each of 3 different SMZ configurations. However, the majority of this study involved only one replicate of the treatments. Table 2.1 details the treatment configurations used. Treatment 1, referred to as 55ft-50%, had a 55 ft harvesting equipment buffer on the perennial stream section with canopy (dominant and codominant crown class) retention of 50%, a 25 ft buffer on the intermittent stream section with no canopy retention, and no buffer on the ephemeral channels with no canopy retention. There were no restrictions on ephemeral channel crossings in the 55ft-50% treatment. Treatment 2, referred to as 110ft-100%, contained 110 ft buffers on the perennial stream sections with 100% canopy retention, 50 ft buffers on the intermittent stream sections with 25% canopy retention, and 25 ft buffers on the ephemeral channels with retention of channel bank trees. Harvest machines were required to use improved stream crossing techniques within the 110ft-100% treatment, including steel pipes, PVC pipe bundles, and portable wooden skidder bridges. Treatment 3, referred to as 55ft-100%, was a hybrid of the 55ft-50% and 110ft-100% treatments, prescribing a 55 ft buffer on the perennial stream section with 100% canopy retention, a 25 ft buffer on the intermittent stream section with 25% canopy retention, and no buffers on the ephemeral channels but with retention of the channel bank trees. Harvesting machines were required to use improved stream crossings in the 55ft-100% treatment, as in the 110ft-100% treatment.

Table 2.2 contains a summary of the Robinson Forest Streamside Management Zone project, including treatment, acres, products removed, harvest operator, harvest equipment used, length and acres of skid trail system, acres of landings, and number of water control structures. Forest harvest operations commenced in early June of 2008 and were complete by the end of October 2009. Harvest operations were carried out by two logging contractors. These two contractors used a similar suite of mechanized harvesting equipment, including chainsaws, rubber-tired wheeled log skidders, bulldozers, tracked swing-arm feller-bunchers, knuckleboom loaders, and an array of 10-wheeled and 18-wheeled haul trucks. All timber was skidded uphill to log decks located on the tops of ridges, where it was sorted and loaded onto the haul trucks for transport to mills. University of Kentucky researchers and forest management personnel had input on the location of the log decks, haul routes, and forest access points, while the design of the skid trail layout for each harvest boundary was solely at the discretion of the logging contractor.

II.2.iii. Field surveys, GPS tracking of harvest, GIS analysis

Before the initiation of forest harvest, MultiDAT Jr. GPS receivers (Castonguay Electronique, Longueuil, Quebec, Canada) were installed on all mobile harvesting equipment. Funding was only sufficient to provide enough MultiDAT GPS receivers to fully outfit one contractor's equipment. Therefore, only three of the six SMZ project harvest watersheds were incorporated into the sediment path and stream crossing studies. One watershed each from the 55ft-50%, 110ft-100%, and 55ft-100% treatments was used; however, information from both unharvested control watersheds was included. The

suite of equipment used by the logging contractor and outfitted with MultiDAT GPS receivers (table 2.2) included a rubber-tired grapple skidder (Caterpillar 545); a rubber-tired cable skidder (Caterpillar 525); three bulldozers (John Deere 650, 700, and 850); a Timbco 445EXL tracked swing-arm feller-buncher; and two Barko knuckleboom loaders (160 and 255). Loaders were equipped with MultiDAT units that recorded operational time information but did not take GPS positions, as the machines were stationary at the landing. All GPS-equipped MultiDATs were set to take a GPS position every 30 seconds while the machine was in motion and working. A maximum vibration threshold was set for each machine while the machine was running but not in motion or working; any level of machine use below this threshold did not result in GPS positions being logged. MultiDAT data was retrieved approximately weekly using an iPAQ Pocket PC (Hewlett-Packard Company, Palo Alto, CA), and downloaded into MultiDAT version 5.1.3 software. GPS positions were exported using the MultiDAT software into the ArcGIS shapefile format for analysis with versions 9.2 and 10 of ArcGIS Desktop (ESRI, Redlands, CA).

A map of the harvest and control watersheds was created in the ArcMap component of ArcGIS, and was populated with the layers and shapefiles necessary to perform analysis of the sediment path and stream crossing data obtained during the studies. Topographic quadrangles and digital elevation models covering the area of Robinson Forest where these studies were performed were obtained from the Kentucky Division of Geographic Information (Kentucky Division of Geographic Information 2006) while other raster data used for analysis were created specifically for this study or were obtained from the

Robinson Forest GIS archives. Shapefiles produced from GPS input were created using a Trimble GeoXM handheld GPS unit with the GPScorrect differential correction extension (Trimble Navigation Limited, Sunnyvale, CA) running ArcPad 7.0 (ESRI, Redlands, CA). Shapefiles created by GPS field surveys included harvest and control watershed boundaries, maps of the forest road and skid trail system, locations of log landings, water control structures installed by the logging contractors, stream crossing locations and associated water sampling points, and harvest watershed access points.

After completion of the harvest and retirement of all skid trails, landings, and haul roads, all perennial, intermittent, and ephemeral stream sections within the three harvested watersheds and the two unharvested control watersheds were scouted for overland sediment delivery pathways that contacted streams. Each of these pathways was characterized using several measures including:

- width where the path contacted the stream,
- slope distance from the source to the stream,
- slope degree,
- source type (primary, secondary, or tertiary skid trail; haul road; general harvest area; sediment flow not associated with visible indications of harvest activity on the forest floor),
- skid trail morphology at source (whether the sediment path began at a sloping section of skid trail, at a relatively flat section (less than 3 degrees or 5% slope), or at a low point where the grade of the skid trail had a positive slope in both directions), and

- water control structure influence (whether a water control structure [waterbar, dip, or berm cut] was present at the source of the sediment path and contributing to sediment flow).

Sediment paths were GPS located, using a Trimble GeoXM handheld GPS unit. If signal strength was not sufficient to obtain a GPS fix, sediment paths were plotted on the GeoXM based on pacing from the last GPS fix. Information on a sediment path's association with an analysis unit (discussed below) was entered, as well as the treatment number of the harvest or control watershed, and a code to distinguish whether the sediment pathway originated inside or outside of the SMZ. All of the above variables were entered into an ArcGIS shapefile attribute table, then exported to a Microsoft Excel spreadsheet (Microsoft Corporation, Redmond, WA).

Though differences in the character of sediment delivery pathways were observed in this study, field crews were unable to reliably distinguish between the different forms of erosional processes operating at each pathway site. As May (2007) describes, there are three major forms of erosion operating in forests: earth flows, which are “large, deep-seated landslides that have complex forms of movement, including block gliding, slumping, and viscous flowing”; gully erosion, which occurs when rills and gullies form from excess surface water running off when rainfall exceeds infiltration; and debris flows, which are channelized mass movements that mobilize stored material. Though all three types were observed during this study, the processes graded into each other such that it was difficult to distinguish a deep gully from a debris flow, or to tell if a particular path was formed by an earth flow caused by block failure or by a debris flow that washed

out its own banks. This being the case, all sediment delivery paths were lumped together, and the relative magnitude of actual sediment delivered to the stream can only be determined from the width of the debris flow where it entered the stream. With so many sediment paths to document and the large area of the study to cover, this was the only feasible method. While further study of overland sediment delivery paths would benefit from separating the paths into types associated with the particular process operating at each path, this was not possible here.

It is important to discuss further the difference between those sediment paths that were documented as originating from areas of the forest floor that were obviously disturbed by the activity of harvest machinery, and those that originated from areas of the forest floor that were not obviously disturbed by the activity of harvest machinery. As field crews documented the source of each sediment path, they carefully inspected the source of the sediment path for indications that forest harvest machinery had operated in the area. If this was the case, the sediment path was recorded as associated with machine activity, and the source was listed as a skid trail, haul road, or as coming from the general harvest area (for example, where the feller-buncher had traveled off trail). These sediment paths are referred to as machine-caused sediment paths throughout the remainder of this study. If the source of the sediment path was from an area of the forest floor that had not been obviously visibly disturbed by the operation of harvest machinery, it was recorded as coming from an area of forest floor undisturbed by machine activity. This type of sediment path is referred to as an undisturbed sediment path throughout the remainder of this study. It should be noted, however, that referring to a sediment path as “undisturbed”

does not imply that other harvesting associated disturbance in the area had nothing to do with the origination of the sediment path. It is possible, even likely, that removal of the forest canopy, for example, has an effect on sediment path origination due to the reduction in rainfall interception by the canopy and a corresponding increase in soil moisture. A sediment path originating from a location such as this that did not display obvious signs of harvest machine activity on the forest floor would be documented as undisturbed because of the lack of obvious visible machine-associated disturbance, not the lack of all harvest disturbance whatsoever.

To enable analysis of environmental and operational variables associated with the initiation of overland sediment delivery pathways, experimental analysis units were roughly rectangular plots of sloping land area bordering stream segments created as polygon shapefiles in ArcMap. Figure 2.3 shows the eleven units analyzed for harvest watershed 3 as an example, while figure 2.4 is a close up of an analysis unit in watershed 3 along the lower perennial section of stream. Each unit encompassed a section of perennial, intermittent, or ephemeral stream, the ground slope directly above this section of stream, and the segments of the skid trail network directly upslope from the stream section. All units in the harvest watersheds were drawn to encompass at least one section of primary skid trail in order to ensure that each unit had sufficient machine traffic to warrant analysis. Analysis units were drawn without reference to the GPS locations of known overland sediment delivery pathways, so as not to bias the number and character of pathways within analysis units. For the unharvested control watershed Little Millseat, experimental units were drawn to encompass sections of the existing forest road system,

in a similar fashion to the units drawn for the harvested watersheds. For the unharvested control watershed Falling Rock, experimental units did not encompass skid trails or forest roads, as these do not exist near the stream in Falling Rock as they do in the other watersheds. Ephemeral drainages entering the main stream channel were avoided when creating the units, as the sediment delivery in these is of a different nature, and will be analyzed in the stream crossing study. Natural landscape breaks were used in creating the experimental units (i.e. spots where ephemeral channels entered on the perpendicular, locations where the stream type changed, etc.). Units were created so as to encompass the slope area above the section of primary skid trail to a line midway between that trail and the primary trail directly upslope. Creating the units in this fashion allowed inclusion of GPS positions that were plotted above the skid trail of interest due to GPS positional error, effectively assigning the inter-trail GPS positions to the trail on which they most likely occurred.

An attribute table for the harvested and control experimental units was created in ArcMap to characterize each experimental unit as to the variables that may have had an influence on overland sediment delivery pathway initiation within that unit. For each harvested experimental unit, treatment-prescribed buffer width and canopy retention percent were entered, as well as treatment designation number 0, 1, 2, or 3. Experimental unit acreage was calculated using the calculate geometry tool in ArcMap. The length of the stream section associated with each unit was determined with the measure tool in ArcMap. Average and maximum slope degree values for each unit were derived from 10 meter digital elevation model (DEM) data. Average aspect for each unit, derived from the 10

meter DEM, was transformed to a moisture index from 0 to 2, with 0 representing the driest slopes (southwest exposure) and 2 representing the wettest slopes (northeast exposure), with a value of 1 representing a slope facing either northwest or southeast and hence an intermediate moisture index (Beers, Dress et al. 1966). The total number of harvest machine traffic GPS positions present within the experimental unit border was entered into the attribute table as a total traffic intensity value for that unit. An index value of machine traffic intensity was calculated by dividing this total traffic intensity value by the area of the unit in acres. The total machine traffic intensity value was broken up into traffic intensities associated with skidder, dozer, and feller-buncher traffic within each unit and entered into the attribute table; index values for each machine type were calculated as above, dividing the total number of GPS positions within an experimental unit associated with each type of machine by the acreage of the unit. Skid trail distances were measured within each unit using the measure tool in ArcMap, and calculated as feet of primary skid trail, secondary skid trail, tertiary skid trail, and total feet of skid trail (table 2.3). A skid trail density index value was calculated by multiplying the total feet of skid trail within each unit by 16 (an average skid trail width throughout the harvest units), then dividing the total square feet of skid trail within the analysis unit by the area of the unit in acres, yielding a value of square feet of skid trail per acre. The minimum distance from a skid trail within the unit to its associated stream section was derived using the measure tool in ArcGIS. A post-harvest residual basal area value for each experimental unit was determined by field measurement using a 10 factor prism at regularly spaced upland and SMZ locations within each unit. An average upland basal area and an average

SMZ basal area were calculated, then those two values were averaged to get the average post-harvest residual basal area for that experimental unit.

A surface roughness value (based on logging debris in contact with the ground surface) between the skid trail and the stream section in each unit was determined by field observation of the ground surface using a measuring tape stretched from the skid trail to the stream edge. At each 10 ft interval on the tape, field personnel documented the presence and characteristics of logging slash in contact with the forest floor directly under the measuring tape. Fine branch slash was defined as those pieces of wood less than or equal to 4 inches in diameter, while coarse branch slash was defined as those pieces of wood greater than 4 inches in diameter (Harmon and Sexton 1996). Each instance where slash of any type (fine, coarse, or a mixture) was documented on the ground surface was assigned a value of 1 (table 2.4), while instances lacking logging slash were assigned a value of 0. The number of instances of slash presence was totaled, then divided by the number of data points along the ground surface from the skid trail to the stream in order to facilitate comparison of varying hillslope distances. The surface roughness values occurring within each analysis unit were then averaged to yield a surface roughness value for that analysis unit. The same process was repeated, but altering the values so that only fine slash was valued as 1 with coarse and mixed being 0; with coarse valued as 1 and fine and mixed being 0; and with mixed as 1 with fine and coarse being 0. This enabled modeling of the importance of total, fine, coarse, and mixed logging slash surface roughness independently.

The response variables for the experimental units were the number and total width of sediment paths reaching the stream in each of the harvested and control experimental units. The number of sediment paths arising within the unit and entering the associated stream section was determined from the sediment path GPS data and entered into the attribute table as either the total number of machine-caused sediment paths or as the total number of undisturbed sediment paths. The total width of each type of sediment path entering the stream section within the unit was also determined from the sediment path GPS data. Each of these values was divided by the total feet of stream adjoining the analysis unit and then multiplied by 1,000 to yield values for the number of sediment paths associated with machine activity (machine-caused) and not associated with machine activity (undisturbed) per 1,000 ft of stream, and the total width of machine-caused and undisturbed sediment paths per 1,000 ft of stream. The proportion of machine-caused sediment paths associated with a water control structure at the source of the path was calculated for each unit with at least one sediment path.

For each unharvested control unit, many of the same values were calculated. However, there were some differences in the specific variable values obtained for the control units as opposed to the harvested units, as well as differences between variables obtained for the two control units. Buffer width was not entered into the shapefile attribute table for the analysis units in the control watersheds, as there was no harvesting within these units and no actual buffer strip. Canopy percent retention was valued at 100% for all control experimental units, while treatment number was designated as 0. Area of each experimental unit was calculated as above with the calculate geometry tool in ArcMap,

with average and maximum slope of each unit determined from 10 meter DEM data, as well as a moisture index with a value of 0 to 2 as was used for the harvested units. Total traffic intensity, traffic intensity by harvest machine type, and area index values of these traffic intensities were not calculated for the control experimental units, as there was no harvest machine traffic in the control watersheds. While there was no harvesting equipment in the control watersheds, Little Millseat did possess a road and trail network that included light duty roads and older abandoned skid trails, constructed in the 1960s. Some of these had been abandoned since construction and initial use and some were still open to slight and sporadic trafficking. The values for feet of trail within those units were entered into the attribute table as a tertiary skid trail. These light use road sections within Little Millseat were covered with leaf litter and some grasses, and therefore most closely mimic the erosional dynamics of unbladed tertiary skid trails, rather than the bladed and more highly erodible primary and secondary skid trails. Total feet of skid trail, trail density as square feet of trail per acre, and minimum distance from trail to stream were calculated as above for the harvested units. The Falling Rock control watershed differed from Little Millseat, and from the harvested watersheds, in that there are no modern road or trail sections within the experimental units in Falling Rock, and therefore no values for feet of trail, trail density, or minimum distance from trail to stream. As in the harvested watersheds, an average total basal area value corresponding to the post-harvest residual basal area of the harvested watersheds was determined for the control watershed experimental units by field measurement using a 10 factor prism at regularly spaced upland and streamside locations within each unit. An average upland basal area and an average streamside basal area were calculated, then those two values were averaged to

get the average basal area for that experimental unit. A value for surface roughness starting from the stream bank and continuing upslope for 200 ft in each unharvested experimental unit was calculated by field observation of the ground surface, using the same protocol as for the harvested units, with the obvious difference that the woody debris on the ground surface was all of natural origin and not associated with logging activity. For the unharvested control watershed Little Millseat, surface roughness was not measured within the 3 analysis units occurring on ephemeral channels, so a mean value obtained from the intermittent and perennial analysis units was used for each type of surface roughness within those 3 units.

As was the case with the harvested watersheds, the response variables for the control watersheds were the number and width of overland sediment flow paths arising within each experimental unit and reaching the associated stream section. Again, as the control watersheds were unharvested, there are no values for harvesting induced sediment paths, and sediment paths were classified as undisturbed. For the undisturbed sediment paths, total number within each experimental unit per 1,000 ft of stream and total width of sediment paths within each unit per 1,000 ft of stream were calculated, as above for the harvested units.

II.2.iv. Data analysis

Figure 2.5 shows a map of the 9 analysis units (3 ephemeral, 3 intermittent, and 3 perennial) for the 55ft-50% treatment. Figure 2.6 shows a map of the 24 analysis units (10 ephemeral, 10 intermittent, and 4 perennial) for the 110ft-100% treatment. Figure 2.7

shows a map of the 11 analysis units (3 ephemeral, 4 intermittent, and 4 perennial) for the 55ft-100% treatment. Figure 2.8 shows a map of the 13 analysis units (3 ephemeral, 6 intermittent, and 4 perennial) for control watershed Little Millseat. Figure 2.9 shows a map of the 20 analysis units (10 ephemeral, 6 intermittent, and 4 perennial) for control watershed Falling Rock. Table 2.5 summarizes the number and type of analysis units for each of the harvest and control watersheds.

All statistical analysis was performed using JMP version 9 (SAS Institute Inc., Cary, NC). Means separation was carried out by the Tukey-Kramer honestly significant difference test, due to the unequal sample sizes involved in this study. Linear models and linear regressions were used in order to determine significant factors in sediment path initiation, and were created by the standard least squares procedure, with pairwise multivariate analyses run to identify and eliminate highly correlated variables. Matched pair analysis was used to determine if the mean number of undisturbed sediment paths per 1,000 ft of stream was significantly greater or less than the mean number of machine-caused sediment paths per 1,000 ft of stream by stream type, as well as to determine if the mean total width of undisturbed sediment paths per 1,000 ft of stream was significantly greater or less than the mean total width of machine-caused sediment paths per 1,000 ft of stream by stream type. As the study area was quite large with a high degree of micro- and macrotopographic diversity, significance was set at the $\alpha=0.10$ level, in order to capture indications of significance that would be missed at the $\alpha=0.05$ level. In many instances, significance levels above $\alpha=0.10$ are discussed when they are slightly above that level, and when trends in nearly significant variables are notable.

II.3. Results and discussion

II.3.i. Performance of MultiDAT GPS dataloggers during harvest operations

The MultiDAT GPS dataloggers performed quite well under the adverse conditions associated with forest harvesting. They were exposed to all weather conditions and temperature extremes, as well as constant vibration, and needed minimal attention to keep running. The units seemed to perform equally well under dense canopy and out in the open, though this is difficult to quantify without the ability to post-process the GPS data. The most frequent cause of MultiDAT malfunction was associated with the GPS antenna wire being cut by abrasion of logging slash. Using heavy duty packing tape to affix the antenna wire to the cab or rollcage of the machine prevented this from happening after the first few instances. Antenna wire breakage caused the loss of only around 10 days of GPS locational data over the course of the nearly 18 months of forest harvest, and was distributed among the machines fairly equally. Therefore, no attempt was made to account for or recreate this lost data.

A total of 680,227 GPS locations were recorded during the course of the harvest of the three Shelly Rock Fork watersheds studied here. Of this total, 272,303 locations were associated with bulldozer activity, 127,821 with feller-buncher activity, and 280,392 with skidder activity.

GPS locations obtained from the MultiDAT units, when plotted on a topographic map, lined up well with the GeoXM-captured skid trails (figure 2.10). Though some GPS locations appear scattered far from a skid trail, the vast majority of locations line up near

a skid trail, and are thus easily assigned to an analysis unit surrounding that section of skid trail. A raster map was created in ArcGIS to show the relative traffic intensity for all harvest machines along the skid trail network (figure 2.11). By setting the raster cell size to 15 ft by 15 ft and the value of each raster cell equal to the total number of harvesting equipment GPS locations that fell within that cell, the map shows traffic intensity along the skid trail network by means of color, where yellow is least trafficked, orange is more trafficked, and red is the most trafficked trail sections. In this way, a useful visual representation of the activity of the mobile harvesting machines can be created. While the raster map shown in figure 2.11 combines traffic intensity data from all harvesting equipment, similar maps were created for the skidders (figure 2.12), bulldozers (figure 2.13), and feller-buncher (figure 2.14). From these traffic intensity maps, one can immediately see which skid trails had the most traffic, where the landings were located during the harvest, and the general pattern of traffic for each equipment type. For example, it is clear that the skidders stayed mainly on the major skid trails and performed out and back trips to pull logs to the landing from staging areas, while the bulldozers and feller-bunchers were more likely to work for longer periods of time in areas of concentrated timber volume, only pulling logs short distances to temporary staging areas. As can be seen from figure 2.14, the feller-buncher spends a good portion of its time traveling along the skid trails, but can work uphill and downhill from the skid trail system along fairly steep slopes, and tends to only be used in areas with sufficient merchantable timber volume. Use of the feller-buncher in areas of low timber quality and volume is not feasible due to the high fuel cost associated with its use. One can also see that bulldozers

are heavily relied upon in the steep terrain of the Cumberland Plateau, especially along the steep lower slopes where the feller-buncher is unwieldy.

The MultiDAT GPS dataloggers, then, are an effective tool to obtain a useful representation of machine traffic during forest harvest. While individual GPS locations may not be reliable to pinpoint the exact location of a given machine at a particular time due to positional errors common to all GPS devices, the overall pattern of machine movement, along with the intensity of that movement along certain sections of skid trail, can be visualized by forest managers. The MultiDAT units also return useful information on machine running time that could be used in an economic analysis of harvest efficiency, though that analysis is outside the scope of this study.

II.3.ii. Machine-caused overland sediment delivery pathways

II.3.ii.a. General characteristics of machine-caused sediment paths

There were a total of 72 overland sediment delivery pathways (sediment paths) recorded in the three harvested watersheds that were associated with the activity of forest harvesting machines (table 2.6), all of which originated from a skid trail and delivered sediment to the section of stream downslope. Those sediment paths that did not reach the stream section, and hence were not implicated in introducing sediment to the stream network, were not recorded for this study.

The control watersheds contained no machine-caused sediment paths. The 55ft-50% treatment contained 23 of the 72 machine-caused sediment paths, 11 of which terminated

at ephemeral channels, 12 of which terminated at intermittent channels, and none of which terminated at perennial channels. The 110ft-100% treatment contained 17 of the 72 machine-caused sediment paths, 7 of which terminated at ephemeral channels, 9 of which terminated at intermittent channels, and 1 of which terminated at a perennial channel. The 55ft-100% treatment contained 32 of the 72 machine-caused sediment paths, 11 of which terminated at ephemeral channels, 6 of which terminated at intermittent channels, and 15 of which terminated at perennial channels.

Of these 72 machine-caused sediment paths, the minimum width of a path was 0.6 ft, the maximum width was 32.8 ft, and the average width was 7.7 ft. As there was no practical way to measure the actual volume of sediment introduced to the stream section by a sediment path in this study, the width of a path was used as a proxy for the magnitude of sediment delivered to the stream, assuming that a wider path would deliver more sediment.

The minimum distance from the point of sediment delivery into the stream to the source of the machine-caused sediment path was 8 ft, the maximum distance was 189 ft, and the average distance was 67.7 ft. 48 of 72 sediment paths (67%) originated from greater than 50 ft from the stream. The minimum degree of slope along which a machine-caused sediment path delivered sediment was 25 degrees, the maximum degree of slope was 48 degrees, and the average degree of slope was 34.1 degrees. This reflects the generally steep character of the slopes near streams in this region of the Cumberland Plateau. Linear regression was used to determine if the degree of slope of the hillside was related

to the length of the machine-caused sediment paths (figure 2.15). Though intuitively this would seem to be the case, the correlation between slope degree and machine-caused sediment path length from source to stream was very weak ($R^2=0.0829$). In a study at the Coweeta Hydrologic Laboratory, Swift (1986) found that sediment transport distance increased with increasing land slope, and that slope was the most important predictor of transport distance. However, that study documented all sediment paths that began from the forest road system whether or not the paths actually reached the stream network, while this study only documented those paths that delivered sediment to the stream network, which may be a factor in the differing results. Also, in this study, the steep slopes from the lower skid trails to the streams are all very similar in grade and morphology, which may not have provided sufficient variability to adequately determine the effect of slope degree on sediment path length.

The origin of these 72 machine-caused sediment paths was as follows: 35 of 72 paths originated from a primary skid trail, 35 of 72 paths originated from a secondary skid trail, and only 2 of 72 paths originated from a tertiary skid trail (figure 2.16). This is to be expected, as tertiary skid trails are non-bladed (table 2.3), and hence do not have the exposed soil surface capable of delivering sediment downhill as primary and secondary skid trails do.

II.3.ii.b. Water control structure influence on sediment paths

Interestingly, 100% of the recorded machine-caused sediment paths were associated with a water control structure installed by the loggers. Though the intent of water control

structures is to divert water off of trails and roads and onto the undisturbed forest floor, this study shows that poor placement of these water control structures can actually increase the chances of sediment delivery to the stream network. Table 2.7 details the total number of water control structures documented within the experimental analysis units of the three harvested watersheds, how many of these were associated with initiation of a machine-caused sediment path, and the percentage of sediment path producing structures out of the total number.

Reverse grade structures, including waterbars and broad-based dips, were by far the most commonly used water control structure in the three harvested watersheds, with a total of 479 documented as falling within an analysis unit. 68 of these 479 reverse grade structures (14.2%) were associated with a sediment path reaching the stream.

Of these, 155 were placed along a relatively flat section of skid trail (less than 3 degrees or 5% slope), with 13 of these (8.3%) producing a sediment path that flowed downhill and reached the stream. These relatively flat trail sections have a larger trail surface area draining from the reverse grade structure, and thus the velocity of the water draining is low but the volume is high, allowing sediment-laden water to overcome the SMZ and reach the stream. Subsurface flow of water in macropores and channels, exposed by the construction of skid trails across the slope, also may contribute to the amount of water available to concentrate and flow from the skid trail to the stream from these reverse grade structures. A relatively flat section of skid trail would expose a larger portion of the

cutbank than a sloping section, increasing the chance of hitting these subsurface flow channels and increasing the volume of water available along that section of skid trail.

Field crews inspected each of these 155 reverse grade structures, and found that only two of them were visibly badly constructed. One of these was at too perpendicular of an angle across the skid trail allowing water to pool behind it and not disperse, and the other was at a flat angle and also was not tied into the road bank, allowing water to flow past the structure without dispersing onto the forest floor. However, the poor construction of these two reverse grade structures did not necessarily lead to sediment path development.

Twelve of these 479 reverse grade structures were constructed at the low point of a skid trail (positive skid trail slope in both directions from the waterbar). Ten of these 12 were associated with a sediment path reaching the stream, meaning that 83.3% of reverse grade structures located at a low point of a skid trail produced sediment paths that reached the stream. None of these reverse grade structures were poorly constructed by themselves, but siting them at a low point allowed water to concentrate along the trail slope from both directions. These low points of the trail system have more surface area to collect a larger volume of water that must be drained by each water control structure. When this water hit the reverse grade structure, it was sufficient to overcome the SMZ and deliver sediment to the stream, while the spacing of the reverse grade structures did not account for the initiation of sediment paths. Sediment paths associated with reverse grade structures located at low points of the skid trail network ranged from 39 ft to 144 ft in length from initiation point to entry into the stream, with an average of 87.5 ft. This indicates that

regardless of slope distance from sediment path source to the stream network, the vast majority of reverse grade structures located at low points produced a sediment path that reached the stream network.

Of the total 479 reverse grade structures, there were 312 structures constructed along a sloping section of skid trail, with 45 of these (14.4%) producing a sediment path that reached the stream. Of these 312 reverse grade structures, 6 were documented as incorrectly installed, either by not being angled correctly across the skid trail, or by being blocked to not allow drainage. However, these construction issues did not necessarily lead to sediment path development. Figure 2.17 shows a histogram of the frequency of sediment paths by slope degree of the skid trails where the paths originated. It is interesting to note the fairly normal distribution of sediment paths by slope degree, where the majority of sediment paths come from skid trails with slope of 11 to 20 degrees (mean slope was 15.3 degrees). This may indicate that along the trail sections with lower slopes, the volume and velocity of moving water is lower and more easily dispersed by water control structures, while at the upper end of the trail slopes, the loggers were more likely to compensate with a denser concentration of water control structures which effectively dispersed water along the skid trails. The middle range of slopes, however, may not stand out as needing extra attention when retiring these sections of skid trail, leading to the water control structures being placed too far apart to effectively control the water flowing along the skid trails. Care must be taken in the interpretation of this graph, however. The distribution of sediment paths by slope degree of skid trail as in figure 2.17 could simply indicate the distribution of skid trail slope degrees. It may be that because there are more

skid trail sections in the middle range of slope degrees, there are more reverse grade structures, and hence more sediment paths along those skid trail sections. It would be desirable to know the percentage of water control structures producing a sediment path at each of the slope degree categories. However, skid trail slope degree information was not collected at each reverse grade structure location, so this data is not currently available.

Berm cuts were also used to control the flow of water along skid trails. These are places in the berm of fill material along the downhill side of a skid trail where the bulldozer placed a cut to allow water to flow out and disperse downhill. Berm cuts were not GPS located during field surveys of the harvested watersheds, so a total number of berm cuts within the analysis units is not available. However, 4 berm cuts were documented as being the source of sediment paths. Of these, 1 was placed on a flat section of skid trail, 1 was placed along a sloping section of skid trail, and 2 were placed at a low point of a skid trail. As for reverse grade structures, berm cuts placed at a low point of a skid trail were more likely than those placed along flat or sloping sections to be associated with sediment path origination.

These results show that proper location and construction of water control structures are highly important factors in the dispersal of water flows along the skid trail system.

Twelve of the 72 machine-caused sediment paths (16.7%) were caused by placing a water control structure (10 by reverse grade structures, 2 by berm cuts) at a low point of skid trail where there was positive trail slope in both directions. Avoiding placing water control structures at these trail system low points would have prevented a major source of

sediment delivery to the stream system during this harvest. Instead of constructing water control at these low points, structures should be placed along the slopes on both sides of the low points, at a high enough concentration to disperse water flows before they attain sufficient volume and velocity to overcome these structures.

II.3.ii.c. Comparison of machine-caused sediment paths by treatment

Of the 72 machine-caused sediment paths, 50 fell within an analysis unit (table 2.6), wherein environmental and forest harvesting variables and attributes were measured, enabling these variables and attributes to be analyzed for their influence on the initiation of sediment paths from within their borders. The control watersheds contained no machine-caused sediment paths falling within an analysis unit. The 55ft-50% treatment contained 15 of the 50 machine-caused sediment paths falling within an analysis unit, 5 of which terminated at ephemeral channels, 10 of which terminated at intermittent channels, and none of which terminated at perennial channels. The 110ft-100% treatment contained 15 of the 50 machine-caused sediment paths falling within an analysis unit, 5 of which terminated at ephemeral channels, 9 of which terminated at intermittent channels, and 1 of which terminated at a perennial channel. The 55ft-100% treatment contained 20 of the 50 machine-caused sediment paths falling within an analysis unit, 1 of which terminated at an ephemeral channel, 5 of which terminated at intermittent channels, and 14 of which terminated at perennial channels.

Means separation was performed using JMP 9 to determine treatment effect on the mean number of machine-caused sediment paths per 1,000 ft of stream, and the mean total

width (as a proxy for sediment volume) of machine-caused sediment paths per 1,000 ft of stream. Further, means were compared as the differences among treatments by stream type, providing information relative to treatment and channel type.

There was no significant difference ($p < 0.10$) in the number or width of machine-caused sediment paths per 1,000 ft of stream of ephemeral channels (table 2.8). This indicates that the extra protections afforded the ephemeral stream sections in the 110ft-100% and 55ft-100% treatments (see table 2.1), as opposed to no protection by either canopy retention or buffer strip in the 55ft-50% treatment (current Kentucky law), had no discernible effect on preventing machine-caused sediment delivery to these ephemeral stream sections.

There was a significant difference between the 55ft-50% treatment and the 110ft-100% treatment for both number ($p = 0.0280$) and width ($p = 0.0459$) of machine-caused sediment paths on the intermittent stream sections (table 2.8). The 110ft-100% treatment produced both fewer (1.5) and narrower (8.5 ft) machine-caused sediment paths than the 55ft-50% treatment (10.0 and 61.1 ft). This gives some indication that the increased buffer width and canopy retention on the intermittent stream sections from the 55ft-50% treatment (25 ft and 0%) to the 110ft-100% treatment (50 ft and 25%) had an effect on preventing machine-caused sediment delivery to the stream network.

For machine-caused sediment paths in the perennial stream sections, the 55ft-50% treatment and the 110ft-100% treatment were not significantly different as to number (0.0

and 0.4) or width (0.0 ft and 0.9 ft) (table 2.8). However, the 55ft-100% treatment (6.9 and 57.7 ft) was significantly greater than the 55ft-50% treatment as to number ($p=0.0015$) and width ($p=0.0293$), as well as the 110ft-100% treatment as to number ($p=0.0013$) and width ($p=0.0219$).

The differences in both sediment path number and width among treatments for perennial streams was not strictly related to SMZ width as the 55ft-50% treatment and the 55ft-100% treatment were the same SMZ width but were statistically different in respect to both number and width of machine-caused sediment paths. This indicates the potential for a variable other than SMZ width affecting sediment delivery. The greater number and total width of machine-caused sediment paths per 1,000 ft of stream in the 55ft-100% treatment as compared to the 110ft-100% treatment may be attributable to the much greater buffer width of the 110ft-100% treatment, while the canopy retention is the same for both treatments at 100%. Several factors such as aspect or soil moisture, surface roughness, SMZ width, equipment trafficking, slope steepness, and residual basal area could explain treatment differences. In order to determine if the reason for the difference in number and width of machine-caused sediment paths between the perennial stream sections of the 55ft-50% and 55ft-100% treatments was related to lack of surface roughness in the 100% canopy retention SMZ of the 55ft-100% treatment, analysis of surface roughness among treatments was performed. No differences in surface roughness among treatments were observed for total surface roughness, fine branch surface roughness, or mixed coarse and fine branch surface roughness. However there were differences when comparing coarse branch (greater than 4 inches in diameter) surface

roughness among treatments (table 2.9). In the ephemeral channels, the 55ft-50% treatment had higher surface roughness than the 55ft-100% treatment ($p=0.0568$), while intermittent streams showed no differences. The perennial stream sections of the 55ft-50% treatment had greater coarse surface roughness than both the 110ft-100% treatment ($p=0.0560$) and the 55ft-100% treatment ($p=0.0180$). The greater coarse surface roughness in the 55ft-50% perennial stream analysis units as compared to the 55ft-100% perennial stream analysis units may explain the greater number and width of machine-caused sediment paths in the 55ft-100% treatment even though the buffer widths of both treatments are the same. Less canopy retention and more harvesting within the perennial SMZ buffer in the 55ft-50% treatment resulted in greater coarse surface roughness, which in turn led to a reduction in perennial stream sediment delivery between that treatment and the 55ft-100% treatment. In fact, several linear models (detailed in the next section) show that surface roughness, especially coarse surface roughness, is significantly negatively related to sediment path number and width.

II.3.ii.d. Modeling of significant factors in machine-caused sediment path development

Linear model analysis was performed using JMP 9 to determine what environmental and harvesting factors may have been significant in the initiation of machine-caused sediment paths. The objective of modeling was to determine which independent environmental and operational variables were significant and which were not in changes of the response variables. Prediction of number of machine-caused sediment paths in a new sample was

not a specific goal, therefore the prediction equations resulting from modeling will not be reported.

Prior to linear modeling, multivariate analysis was conducted by the pairwise method to identify and eliminate those independent variables that were highly correlated, as correlated variables in the same model can disrupt the correct estimation of variable significance. Table 2.10 details the results of this correlation analysis for the independent variables used in modeling for the harvested watersheds, where all machine-caused sediment paths were located. Canopy retention percent (highly correlated with buffer width [0.8179]) was eliminated as average residual basal area already accounts for canopy retention. Maximum analysis unit slope (correlated with average analysis unit slope [0.7623]) was also eliminated, as the average slope of the analysis unit as a whole should be more important in sediment path development than a singular maximum slope in the analysis unit. Traffic area index for all harvest machines combined showed a relatively high degree of correlation with traffic area index for bulldozers (0.7920) and skidders (0.7119), and little correlation with traffic area index for the feller-buncher (0.3151). Due to this, separate models were created using combined traffic area index, and using the three individual machine type traffic area indices together, as the three individual types were not correlated with each other. Also, fine logging slash presence was correlated with total logging slash presence (0.7804). Because of this correlation and the desire to model the influence of different types of surface roughness individually, separate models were created using total surface roughness (all types combined), and

using the three types of surface roughness (fine, coarse, and mixed) together, as the three individual types were not correlated with each other.

The first model created used the number of machine-caused sediment paths per 1,000 ft of stream as the response variable, and was run for all harvest treatments and stream types (table 2.11). The R^2 value for this model was 0.305014. Independent variables included: SMZ buffer width, average slope of the analysis unit, moisture index, post harvest basal area, total (all types together) surface roughness, combined traffic area index, trail density, and minimum distance from trail to stream. Moisture index ($p=0.0459$) and total surface roughness ($p=0.0606$) were significant in this model, as was minimum distance from trail to stream ($p=0.0947$). Moisture index was positively related to number of machine-caused sediment paths per 1,000 ft of stream; this indicates that on wetter slopes (i.e. more northeasterly slopes), the greater amount of water on and in the soil leads to a greater potential for overland sediment delivery to streams. Total surface roughness was negatively related to number of machine-caused sediment paths per 1,000 ft of stream; this indicates that as the surface roughness increases with the deposition of logging slash on the slope below the skid trail system, there is less potential for overland sediment delivery to streams, as the slash tends to hold some of that sediment back. Minimum distance from trail to stream was also negatively related to number of machine-caused sediment paths per 1,000 ft of stream, so that as the minimum distance from the skid trail network to the stream increases, the potential for overland sediment delivery to the stream decreases, as the sediment would have to flow over a longer distance downslope and would be more likely to be dispersed along the forest floor before

reaching the stream. Combined traffic area index, a measure of the intensity of harvest machine traffic within the analysis units, was not a significant factor in this model.

Running the model with the same set of independent variables, but replacing number with total width of machine-caused sediment paths per 1,000 ft of stream for the response variable, yielded the same pattern of significance (table 2.11). The R^2 value for this model was 0.360031. Moisture index was significantly positively related to total width of machine-caused sediment paths per 1,000 ft of stream ($p=0.0441$), while total surface roughness was significantly negatively related ($p=0.0609$). Minimum distance from trail to stream was even more significantly negatively related to total width of machine-caused sediment paths per 1,000 ft of stream ($p=0.0184$) than it was to number of machine-caused sediment paths per 1,000 ft of stream.

Using number of machine-caused sediment paths per 1,000 ft of stream again as the response variable, but replacing combined traffic area index with the individual machine type traffic area indices while still using total surface roughness, a similar pattern holds (table 2.12). The R^2 value for this model was 0.360296. Moisture index becomes less significantly positively correlated with number of machine-caused sediment paths per 1,000 ft of stream ($p=0.1154$) though still is near significance, while surface roughness retains its significant negative correlation with number of machine-caused sediment paths per 1,000 ft of stream ($p=0.0837$), and minimum distance from trail to stream is still quite near significant negative correlation ($p=0.1080$). It is interesting to note that in this model, traffic area index for feller-buncher is positively correlated with the number of

machine-caused sediment paths, though it is not significantly so ($p=0.1335$). This would seem to indicate that the more feller-buncher traffic occurred in an analysis unit, the more likely it was that sediment paths were initiated and sediment was delivered to the stream, though the result is not significant enough to draw a strong conclusion.

Running the model with the same set of independent variables, but replacing number with total width of machine-caused sediment paths per 1,000 ft of stream for the response variable, the same pattern is obtained (table 2.12). The R^2 value for this model was 0.415576. Moisture index is nearly significantly positively correlated with total width of machine-caused sediment paths per 1,000 ft of stream ($p=0.1153$), total surface roughness is significantly negatively correlated ($p=0.0824$), while minimum distance from trail to stream is significantly negatively correlated ($p=0.0204$). Feller-buncher traffic area index slips in its positive correlation with total width of machine-caused sediment paths per 1,000 ft of stream ($p=0.2135$). One other independent variable makes an interesting entry into the model at this point, however. Skidder traffic area index does not achieve full significance in the model ($p=0.1308$), but it is close. Strangely, though, skidder traffic area index is negatively correlated with total width of machine-caused sediment paths per 1,000 ft of stream. Counterintuitively, it may be that increasing skidder traffic in an area actually compacts the soil and hence leads to less potential for overland sediment flow from the area of compacted soil. The difference between the feller-buncher traffic and skidder traffic in this study may then be due to their means of contact with the ground, as the rubber-tired skidders compact the soil and make it less likely to erode into the streams, while the tracked feller-buncher churns up more soil that can be dislodged by

falling rain and subsequently flow downslope. This theory is not supported by the number of machine-caused sediment paths per 1,000 ft of stream model, however, but is interesting nonetheless. Again, these results are not significant, and though the pattern of correlation is interesting, care should be taken not to draw too strong a conclusion here.

The next four models use fine, coarse, and mixed surface roughness values in place of the total surface roughness value used in the last four models. Running a model using number of machine-caused sediment paths as the response variable, with combined traffic area index and these individual types of surface roughness, we see further support for the significance of moisture index ($p=0.0790$, positive correlation) and minimum distance from trail to stream ($p=0.0810$, negative correlation) (table 2.13). The R^2 value for this model was 0.315648. None of the surface roughness inputs were significant, though coarse surface roughness was close enough to mention ($p=0.1325$) and was negatively correlated. This gives some evidence that larger diameter logging slash left on the ground surface between the trail system and the stream may help to prevent sediment delivery. Keeping all independent variables the same but using width as the response variable, moisture index remains significant ($p=0.0626$, positive correlation), as does minimum distance from trail to stream ($p=0.0275$, negative correlation) (table 2.13).

Replacing combined traffic area index with individual machine type indices and using individual types of surface roughness, with number as the response variable (table 2.14), we once again see minimum distance from trail to stream significantly negatively correlated ($p=0.0827$). Coarse surface roughness comes in just barely above significance

($p=0.1011$, negative correlation), again suggesting that larger diameter logging slash may be effective at reducing sediment delivery. Feller-buncher traffic index attains significance in this model, and is positively correlated with number of machine-caused sediment paths ($p=0.0866$), further supporting the theory mentioned earlier that the tracks of the feller-buncher may churn up the soil and increase the potential for dislodged sediment to flow downhill. The R^2 value for this model was 0.385390. The same model with width as the response variable again (table 2.14) shows the significant negative correlation of minimum distance from trail to stream ($p=0.0242$). This model variation also supports the pattern seen above where skidder traffic is negatively correlated with sediment delivery, though not significantly ($p=0.1469$), while feller-buncher traffic is positively correlated, though also not significantly ($p=0.1496$). The R^2 value for this model was 0.432450.

Finally, it should be noted that any separation of the total harvest machine traffic into traffic by different types of machine, and then drawing conclusions from the individual machine types' traffic levels, is fairly speculative. This study was not done in a manner that allows distinct separation of the different types of machine traffic, i.e. we were not able to run only the skidders in an area, excluding the bulldozers and feller-bunchers, and then document sediment paths that would only be associated with skidder traffic. The GPS data gives us information on the amount of each type of machine traffic in a particular area, but it is not possible to strongly tie each individual type of machine traffic to a certain fraction of the total number of machine-caused sediment paths. However, as the pattern presents itself frequently, it is worth noting as an area for further study where

the individual machine types could be studied independently for their contribution to sediment delivery.

II.3.iii. Undisturbed forest floor overland sediment delivery pathways

II.3.iii.a. General characteristics of undisturbed sediment paths

There were a total of 570 overland sediment delivery pathways recorded in the three harvested and two unharvested control watersheds that were not associated with the activity of forest harvesting machines (table 2.6), all of which originated from areas not visibly disturbed by harvesting activity and delivered sediment to the section of stream downslope. Those sediment paths that did not reach the stream section, and hence were not implicated in introducing sediment to the stream network, were not recorded for this study.

Control watershed Little Millseat contained 166 of the 570 undisturbed sediment paths, 53 of which terminated at ephemeral channels, 64 of which terminated at intermittent channels, and 49 of which terminated at perennial channels. Control watershed Falling Rock contained 234 of the 570 undisturbed sediment paths, 155 of which terminated at ephemeral channels, 52 of which terminated at intermittent channels, and 27 of which terminated at perennial channels. The 55ft-50% treatment contained 45 of the 570 undisturbed sediment paths, 28 of which terminated at ephemeral channels, 9 of which terminated at intermittent channels, and 8 of which terminated at perennial channels. The 110ft-100% treatment contained 79 of the 570 undisturbed sediment paths, 28 of which terminated at ephemeral channels, 31 of which terminated at intermittent channels, and

20 of which terminated at perennial channels. The 55ft-100% treatment contained 46 of the 570 undisturbed sediment paths, 21 of which terminated at ephemeral channels, 22 of which terminated at intermittent channels, and 3 of which terminated at perennial channels.

Of these 570 undisturbed sediment paths, the minimum width of a path was less than 0.1 ft, the maximum width was 88.4 ft, and the average width was 6.3 ft. As there was no practical way to measure the actual volume of sediment introduced to the stream section by a sediment path in this study, the width of a path was used as a proxy for the magnitude of sediment delivered to the stream, assuming that a wider path would deliver more sediment.

The minimum distance from the point of sediment delivery into the stream to the source of the sediment path was 3 ft, the maximum distance was 264 ft, and the average distance was 45.2 ft. 196 of 570 sediment paths (34%) originated from greater than 50 ft from the stream. The minimum degree of slope along which an undisturbed sediment path delivered sediment was 4 degrees, the maximum degree of slope was 74 degrees, and the average degree of slope was 33.1 degrees. This reflects the generally steep character of the slopes near streams in this region of the Cumberland Plateau. Linear regression was used to determine if the degree of slope of the hillside was related to the length of the undisturbed sediment paths (figure 2.18). Though intuitively this would seem to be the case, the correlation between slope degree and undisturbed sediment path length from source to stream was very weak ($R^2=0.0422$).

II.3.iii.b. Comparison of undisturbed sediment paths by treatment

Of the 570 undisturbed sediment paths, 311 fell within an analysis unit (table 2.6), wherein environmental and forest harvesting variables and attributes were measured, enabling these variables and attributes to be analyzed for their influence on the initiation of sediment paths from within their borders. Control watershed Little Millseat contained 67 of the 311 undisturbed sediment paths falling within an analysis unit, 7 of which terminated at ephemeral channels, 36 of which terminated at intermittent channels, and 24 of which terminated at perennial channels. Control watershed Falling Rock contained 141 of the 311 undisturbed sediment paths falling within an analysis unit, 87 of which terminated at ephemeral channels, 32 of which terminated at intermittent channels, and 22 of which terminated at perennial channels. The 55ft-50% treatment contained 21 of the 311 undisturbed sediment paths falling within an analysis unit, 8 of which terminated at ephemeral channels, 5 of which terminated at intermittent channels, and 8 of which terminated at perennial channels. The 110ft-100% treatment contained 45 of the 311 undisturbed sediment paths falling within an analysis unit, 13 of which terminated at ephemeral channels, 23 of which terminated at intermittent channels, and 9 of which terminated at perennial channels. The 55ft-100% treatment contained 37 of the 311 undisturbed sediment paths falling within an analysis unit, 12 of which terminated at ephemeral channels, 22 of which terminated at intermittent channels, and 3 of which terminated at perennial channels.

Means separation was performed using JMP 9 to determine treatment effect on the mean number of undisturbed sediment paths per 1,000 ft of stream, and the mean total width

(as a proxy for sediment volume) of undisturbed sediment paths per 1,000 ft of stream. Further, means were compared as the differences among treatments by stream channel type, providing information relative to treatment and channel type.

Before comparing control to harvest means, however, it was necessary to do a preliminary comparison of the two control watersheds, Little Millseat and Falling Rock. As mentioned above, Little Millseat contains several sections of lightly traveled forest road within its borders, while Falling Rock does not. A comparison of the mean number and mean total width of undisturbed sediment paths per 1,000 ft of stream in the analysis units of each was performed to determine if the two controls actually differed from each other (table 2.15). In only one instance did the two controls differ: in the intermittent analysis units of Little Millseat, the width of undisturbed sediment paths was much larger (173.9 ft) than in the intermittent analysis units of Falling Rock (60.6 ft) ($p=0.0618$). However, this can be explained by two very large landslides in Little Millseat that were counted as sediment paths (388.3 ft and 213.4 ft), and which cause the width to be much higher in Little Millseat. Except for that difference, no measures differ between the two control watersheds, hence the two control watersheds were treated as essentially similar, and were pooled together in comparing control and harvest effects on undisturbed sediment paths.

For the ephemeral stream sections, the mean width of undisturbed sediment paths per 1,000 ft of stream did not differ among any of the treatments (table 2.16), though the number of undisturbed sediment paths was significantly higher ($p=0.0093$) in the control

watersheds (13.6) than in the 110ft-100% treatment (3.3). It is difficult to determine why the mean number of undisturbed sediment paths per 1,000 ft of stream was higher in the control watersheds than in the 110ft-100% treatment, though it is possible that the harvest machine traffic and the more developed skid trail network in the harvest watersheds, with its associated water control structures designed to disperse overland sediment flows before they reached the stream network, actually prevented some of the undisturbed sediment paths from reaching the stream in the harvest watersheds, while similar undisturbed sediment paths in the control watersheds were able to make it to the stream.

For the intermittent stream sections, the mean width of undisturbed sediment paths per 1,000 ft of stream again did not differ among any of the treatments (table 2.16). However, the number of undisturbed sediment paths was significantly higher ($p=0.0216$) in the control watersheds (12.7) compared to the 110ft-100% treatment (3.7), while the number of undisturbed sediment paths in the 55ft-100% treatment (13.6) was significantly higher ($p=0.0867$) than in the 110ft-100% treatment (3.7). Again, it is difficult to determine why the mean number of undisturbed sediment paths per 1,000 ft of stream was higher in the control watersheds than in the 110ft-100% treatment, though the theory discussed above that the skid trail network and its water control structures diverted and dispersed some undisturbed sediment paths before they reached the stream is possible. The greater mean number of undisturbed sediment paths per 1,000 ft of stream in the 55ft-100% treatment as compared to the 110ft-100% treatment can be explained in terms of the larger buffer width in the 110ft-100% treatment intermittent SMZ holding back and helping to disperse some undisturbed sediment paths before they reached the stream network.

For the perennial stream sections, the mean width of undisturbed sediment paths per 1,000 ft of stream once again did not differ among any of the treatments (table 2.16). However, the number of undisturbed sediment paths in the control watersheds (8.0) was significantly greater ($p=0.0908$) than the 110ft-100% treatment (2.8), and significantly greater ($p=0.0195$) than the 55ft-100% treatment (1.2). The greater number of undisturbed sediment paths per 1,000 ft of stream in the control watersheds can again possibly be attributed to the ability of the skid trail network and its water control structures diverting and dispersing some of the undisturbed sediment paths before they reached the stream network.

II.3.iii.c. Modeling of significant factors in undisturbed sediment path development

Linear model analysis was again performed using JMP 9 to determine what environmental and harvesting factors may have been significant in the initiation of undisturbed sediment paths. The objective of modeling was to determine which independent environmental and operational variables were significant and which were not in changes of the response variables. Prediction of number of undisturbed sediment paths in a new sample was not a specific goal, therefore the prediction equations resulting from modeling will not be reported.

Prior to linear modeling, multivariate analysis was again conducted by the pairwise method to identify and eliminate those independent variables that were highly correlated. As undisturbed sediment paths occurred in both the harvested and control watersheds, for modeling of significant factors in undisturbed sediment path development, two analyses

of correlations among independent variables were run. The first analysis was for harvested watersheds using the same full complement of variables used for modeling machine-caused sediment paths, and a second for control watersheds using a reduced complement of variables. The latter was done because some of the harvesting-related independent variables were irrelevant to the control watersheds.

For the harvested watersheds (table 2.10), the process was repeated as above for machine-caused sediment paths: canopy retention percent and maximum analysis unit slope were eliminated, while separate models were created using combined traffic area index and the three individual types of traffic, and separate models were created using total surface roughness and the individual types of surface roughness.

In the control watersheds, only one correlation was found: fine logging slash presence was again correlated with total logging slash presence (0.9394), as above for the harvested watersheds (table 2.10). Therefore modeling using surface roughness was done similarly in the control watersheds, creating separate models for total surface roughness and for the three types of surface roughness together. Buffer width was eliminated as there were no actual buffers in the controls, just uncut forest. Canopy percent was eliminated for a similar reason: canopy was undisturbed in the controls, and was therefore 100% in all units, making it meaningless to the model. Maximum slope was removed from modeling for the reason discussed above, and all traffic area indices were removed from modeling in the control watersheds as the controls had no machine traffic. Trail density and the minimum distance from trail to stream were removed for the Falling

Rock control, as there was no road and trail system within that watershed; however, these were left in the models for Little Millseat, in order to document the influence of the little-used road and trail system that is present in that watershed.

The first model created used the number of undisturbed sediment paths per 1,000 ft of stream for both control watersheds combined as the response variable. Independent variables included: average slope of the analysis unit, moisture index, basal area of the unharvested stand, and total surface roughness. No significance was detected among the independent variables in this model, though average slope of the analysis unit was near significance ($p=0.1150$), and was positively related to number of undisturbed sediment paths per 1,000 ft of stream. Using total width of undisturbed sediment paths per 1,000 ft of stream as the response variable for both control watersheds combined again yielded no significance from any of the variables under consideration.

When running the same model but separating the types of surface roughness (table 2.17), however, average slope of the analysis unit was significant ($p=0.0782$) and positively correlated with number of undisturbed sediment paths. This is evidence that the slope of a site may be important in undisturbed sediment path development. A regression of machine-caused sediment path distance from source to stream with slope showed no relationship, though there may be factors in this study making that relationship hard to detect, as discussed above. Also significant in this model was coarse surface roughness ($p=0.0473$), implying that the larger diameter pieces of logging slash left between the trail system and the stream may be important in preventing sediment delivery. This was

hinted at in the machine-caused sediment path models, but was not significant in those. The R^2 value for this model was 0.268179. When replacing number with width of undisturbed sediment paths, again no variables were significant.

Next, the two control watersheds were separated and models were run for each, due to the trail network present in Little Millseat. A model was created using number of undisturbed sediment paths per 1,000 ft of stream in the Falling Rock control as the response variable, and using these independent variables: average slope, moisture index, basal area, and total surface roughness. No significance was noted in this model (table 2.18), but when running the same independent variables with total width of undisturbed sediment paths per 1,000 ft of stream as the response variable, moisture index showed a significant positive relationship to total undisturbed path width per 1,000 ft of stream ($p=0.0682$), as it did in some of the models for machine-caused sediment paths. The R^2 value for this model was 0.208786. Replacing total surface roughness with the individual surface roughness types yielded no significant variables for either number or width of undisturbed sediment paths in the Falling Rock control watershed.

Modeling for the Little Millseat control expanded the complement of independent variables under analysis: average slope of the analysis unit, moisture index, basal area, and surface roughness were used as in the Falling Rock models, but trail density and minimum distance from trail to stream were also included because of the trail network in Little Millseat. Table 2.19 summarizes these models. Using number of undisturbed sediment paths per 1,000 ft of stream as the response variable, with total surface

roughness, the model showed no variables as significant. When replacing number with total width of undisturbed sediment paths per 1,000 ft of stream as the response variable, trail density showed a significant positive relationship to total undisturbed path width per 1,000 ft of stream ($p=0.0875$). The R^2 value for this model was 0.502644. The positive relationship with trail density shown in the Little Millseat model using total width of undisturbed sediment paths per 1,000 ft of stream as the response variable is the first time trail density showed significance, and it seems counter to the results mentioned above that more of a road and trail network seems to have a preventive effect on undisturbed sediment paths reaching the streams. However, the trail network in Little Millseat has likely degraded over time, and no longer has new and effective water control structures as the trail networks in the harvested watersheds do (data is needed to support this hypothesis, however). This could be the reason that a denser trail network in Little Millseat actually led to an increase in sediment delivery, as the trail network's water control may not be functioning at full capacity.

Those same two models were also run with individual types of surface roughness instead of total surface roughness (table 2.19). With number of undisturbed sediment paths as the response variable, average basal area of the uncut stand was significantly positively related to number of undisturbed sediment paths ($p=0.0922$). Model R^2 was 0.782733. This result may mainly show the significance of aspect and soil moisture, as a higher basal area stand would most likely be located in an area with a more northeasterly aspect with greater soil moisture. With width of undisturbed sediment paths as the response variable, trail density again was once again significantly positively correlated ($p=0.0908$).

Model R^2 was 0.751580. The relationship of trail density to sediment path development in Little Millseat was discussed above.

The next two models (summarized in table 2.20) were run in order to investigate possible significant factors in undisturbed sediment path initiation in the harvested watersheds.

The first model created used number of undisturbed sediment paths per 1,000 ft of stream for the treatment watersheds as the response variable. Independent variables included: treatment-prescribed SMZ buffer width, average slope of the analysis unit, moisture index, post-harvest basal area, total surface roughness, combined (all machine types) traffic area index, trail density, and minimum distance from trail to stream. The R^2 value for the first model was 0.279900. The second model used total width of undisturbed sediment paths per 1,000 ft of stream for the harvested watersheds as the response variable, with the same suite of independent variables. The R^2 value for the second model was 0.242370. Both models showed significance of the same independent variables. SMZ buffer width was highly significant and negatively related to the response variable in both models ($p=0.0059$ with number of undisturbed paths per 1,000 ft of stream, $p=0.0041$ with total width of undisturbed paths per 1,000 ft of stream). This indicates that as the SMZ buffer width got larger, the number and total width of undisturbed sediment paths per 1,000 ft of stream decreased. Though this was not observed in the models for machine-caused sediment paths, this supports the idea that a wider buffer strip enables sediment paths to disperse before they reach the stream network as they move across the SMZ. Combined traffic area index also shows significance in both models, and is negatively related to the response variables ($p=0.0431$ with number of undisturbed paths

per 1,000 ft of stream, $p=0.0498$ with total width of undisturbed paths per 1,000 ft of stream). As discussed above, it is counterintuitive that as harvest machine traffic increases in an area, the number and width of undisturbed sediment paths in that area actually decreases. However, as indicated above, this could be due to the increased machine traffic in an area leading to a trail network with effective water control structures that help to reduce the velocity of sediment paths traveling downslope as well as disperse them over the undisturbed forest floor. The increased soil compaction, especially with rubber-tired skidder traffic, may also have an influence on decreasing the amount of loosely held disturbed soil available to erode downslope. Running the same two models with individual types of surface roughness yields nearly the same pattern (table 2.21). For number of undisturbed sediment paths, the R^2 value was 0.340165, with buffer width showing significant negative correlation ($p=0.0043$), and combined traffic area index nearly significant and negatively correlated ($p=0.1269$). For width of undisturbed sediment paths, the R^2 value was 0.260175, with buffer width again showing highly significant negative correlation ($p=0.0040$), and combined traffic area index also significantly negatively correlated ($p=0.0981$).

Four more models were created to look for significant factors in undisturbed sediment path initiation in the harvested watersheds, using number and total width of undisturbed sediment paths per 1,000 ft of stream as the response variables, but replacing the combined traffic area index independent variable with the individual machine type traffic area indices (table 2.22). Similar results were obtained with these models. Using total surface roughness in the first two models, the R^2 value for the first model was 0.325574,

and 0.302919 for the second model. Buffer width once again showed a highly significant negative relationship to both number and total width of undisturbed sediment paths per 1,000 ft of stream ($p=0.0084$ for number per 1,000 ft of stream, $p=0.0018$ for total width per 1,000 ft of stream). Again, this supports the theory that a wider SMZ more effectively prevents overland sediment delivery to the stream network. The traffic area index for the feller-buncher showed a significant negative relationship to both number and total width of undisturbed sediment paths per 1,000 ft of stream ($p=0.0704$ for number, $p=0.0298$ for total width). This is the opposite result for feller-buncher traffic as was obtained when modeling for machine-caused sediment paths. A possible explanation for this state of affairs may be that though increased feller-buncher traffic, with its tracked form of locomotion that tends to leave more loosely held disturbed soil than wheeled vehicles, increased the chances for sediment paths related to its own traffic, the increased trail network needed for machine traffic associated with the feller-buncher and other machines leads to a more developed water control system and therefore decreases the chances for sediment paths of undisturbed forest floor origin. In the number of undisturbed sediment paths per 1,000 ft of stream model, the traffic area index for bulldozer traffic also showed a significant negative relationship ($p=0.0369$), though the correlation was much weaker in the model for total width of undisturbed sediment paths per 1,000 ft of stream ($p=0.1412$). Given the similar tracked form of movement for the bulldozers as for the feller-buncher, the above possibility applies to bulldozer traffic as well. Using individual types of surface roughness in the next two models, the R^2 value for the first model was 0.365907, and 0.308893 for the second model (table 2.23). Buffer width remained highly significantly negatively correlated with both number and total width of undisturbed

sediment paths ($p=0.0085$ for number, $p=0.0024$ for width). The only significant correlation with type of machine traffic was with feller-buncher traffic in the model using width as the response variable ($p=0.0603$, negative correlation), though the same pattern of negative correlation with feller-buncher and bulldozer traffic holds for both number and width of undisturbed sediment paths, with the same potential explanation.

II.3.iv. Combined machine-caused and undisturbed overland sediment delivery pathways

II.3.iv.a. General characteristics of combined machine-caused and undisturbed sediment paths

There were a total of 642 combined machine-caused and undisturbed overland sediment delivery pathways recorded in the three harvested and two unharvested control watersheds (table 2.6), all of which delivered sediment to the section of stream downslope. Those sediment paths that did not reach the stream section, and hence were not implicated in introducing sediment to the stream network, were not recorded for this study.

Control watershed Little Millseat contained 166 of the 642 combined sediment paths, 53 of which terminated at ephemeral channels, 64 of which terminated at intermittent channels, and 49 of which terminated at perennial channels. Control watershed Falling Rock contained 234 of the 642 combined sediment paths, 155 of which terminated at ephemeral channels, 52 of which terminated at intermittent channels, and 27 of which terminated at perennial channels. The 55ft-50% treatment contained 68 of the 642

combined sediment paths, 39 of which terminated at ephemeral channels, 21 of which terminated at intermittent channels, and 8 of which terminated at perennial channels. The 110ft-100% treatment contained 96 of the 642 combined sediment paths, 35 of which terminated at ephemeral channels, 40 of which terminated at intermittent channels, and 21 of which terminated at perennial channels. The 55ft-100% treatment contained 78 of the 642 combined sediment paths, 32 of which terminated at ephemeral channels, 28 of which terminated at intermittent channels, and 18 of which terminated at perennial channels.

Of these 642 combined sediment paths, the minimum width of a path was less than 0.1 ft, the maximum width was 88.4 ft, and the average width was 6.4 ft. As there was no practical way to measure the actual volume of sediment introduced to the stream section by a sediment path in this study, the width of a path was used as a proxy for the magnitude of sediment delivered to the stream, assuming that a wider path would deliver more sediment.

The minimum distance from the point of sediment delivery into the stream to the source of the sediment path was 3 ft, the maximum distance was 264 ft, and the average distance was 47.8 ft. 244 of 642 combined machine-caused and undisturbed sediment paths (38%) originated from greater than 50 ft from the stream. The minimum degree of slope along which a sediment path delivered sediment was 4 degrees, the maximum degree of slope was 74 degrees, and the average degree of slope was 33.2 degrees. This reflects the generally steep character of the slopes near streams in this region of the Cumberland

Plateau. Linear regression was used to determine if the degree of slope of the hillside was related to the length of the sediment paths (figure 2.19). Though intuitively this would seem to be the case, the correlation between slope degree and combined sediment path length from source to stream was very weak ($R^2=0.039$).

II.3.iv.b. Comparison of combined machine-caused and undisturbed sediment paths by treatment

Of the 642 combined sediment paths, 361 fell within an analysis unit (table 2.6), wherein environmental and forest harvesting variables and attributes were measured, enabling these variables and attributes to be analyzed for their influence on the initiation of sediment paths from within their borders. Control watershed Little Millseat contained 67 of the 361 combined sediment paths falling within an analysis unit, 7 of which terminated at ephemeral channels, 36 of which terminated at intermittent channels, and 24 of which terminated at perennial channels. Control watershed Falling Rock contained 141 of the 361 combined sediment paths falling within an analysis unit, 87 of which terminated at ephemeral channels, 32 of which terminated at intermittent channels, and 22 of which terminated at perennial channels. The 55ft-50% treatment contained 36 of the 361 combined sediment paths falling within an analysis unit, 13 of which terminated at ephemeral channels, 15 of which terminated at intermittent channels, and 8 of which terminated at perennial channels. The 110ft-100% treatment contained 60 of the 361 combined sediment paths falling within an analysis unit, 18 of which terminated at ephemeral channels, 32 of which terminated at intermittent channels, and 10 of which terminated at perennial channels. The 55ft-100% treatment contained 57 of the 361

combined sediment paths falling within an analysis unit, 13 of which terminated at ephemeral channels, 27 of which terminated at intermittent channels, and 17 of which terminated at perennial channels.

Means separation was performed using JMP 9 to determine treatment effect on the mean number of combined sediment paths per 1,000 ft of stream, and the mean total width (as a proxy for sediment volume) of combined sediment paths per 1,000 ft of stream. Further, means were compared as the differences among treatments by stream channel type, providing information relative to treatment and channel type. Comparison of means for combined sediment paths per 1,000 ft of stream was carried out by comparing the harvested watersheds only, as the control watersheds had no machine-caused sediment paths within their borders, and an analysis of combined sediment paths in the control watersheds would be identical to the previously done analysis of their undisturbed sediment paths. Means were compared as the differences among treatments by stream type.

For the ephemeral stream sections, the mean number of combined sediment paths in the 110ft-100% treatment (4.5) was significantly less ($p=0.0484$) than the 55ft-50% treatment (12.2), and was also significantly less ($p=0.0969$) than the 55ft-100% treatment (11.1) (table 2.24). The mean width of combined sediment paths in the 55ft-50% treatment (150.4 ft) was significantly greater ($p=0.0590$) than the 110ft-100% treatment (28.2 ft). The greater number of combined sediment paths in the 55ft-50% and 55ft-100% treatments compared to the 110ft-100% treatment indicates that the presence of an SMZ

buffer on the ephemeral stream sections of the 110ft-100% treatment helped to prevent sediment delivery to the ephemeral streams in that treatment. The greater width of combined sediment paths in the 55ft-50% treatment compared to the 110ft-100% treatment supports this hypothesis as well.

For the intermittent stream sections, the mean number of combined sediment paths in the 110ft-100% treatment (5.2) was significantly less ($p=0.0205$) than the 55ft-50% treatment (16.0), and was also significantly less ($p=0.0051$) than the 55ft-100% treatment (17.1) (table 2.24). The width of combined sediment paths in the 110ft-100% treatment (49.0 ft) was significantly less ($p=0.0051$) than the 55ft-100% treatment. The greater number of combined sediment paths in the 55ft-50% and 55ft-100% treatments compared to the 110ft-100% treatment indicates that the wider SMZ buffer on the intermittent stream sections of the 110ft-100% treatment helped to prevent sediment delivery to the intermittent streams in that treatment. The greater width of combined sediment paths in the 55ft-100% treatment compared to the 110ft-100% treatment also supports the hypothesis that the wider SMZ buffer in the 110ft-100% treatment helped to prevent sediment delivery to the intermittent stream sections in that treatment, though canopy retention levels were the same for the 110ft-100% and 55ft-100% treatments.

For the perennial stream sections, there were no significant differences among treatments for either number or width of combined sediment paths, though the width of combined sediment paths in the 110ft-100% treatment (11.6) was nearly different ($p=0.1059$) from the 55ft-100% treatment (62.6) (table 2.24). Though there were no significant differences

detected for the perennial stream sections among treatments, the analysis did indicate a trend of the 110ft-100% treatment having fewer and narrower combined sediment paths than the other treatments, possibly due to the wider perennial stream SMZ buffers.

II.3.iv.c. Modeling of significant factors in combined machine-caused and undisturbed sediment path development

Linear model analysis was again performed using JMP 9 to determine what environmental and harvesting factors may have been significant in the initiation of combined sediment paths. The objective of modeling was to determine which independent environmental and operational variables were significant and which were not in changes of the response variables. Prediction of number of combined sediment paths in a new sample was not a specific goal, therefore the prediction equations resulting from modeling will not be reported.

Linear modeling of combined sediment paths per 1,000 ft of stream was carried out by modeling the harvested watersheds only, as the control watersheds had no machine-caused sediment paths within their borders, and modeling of combined sediment paths in the control watersheds would be identical to the previously done modeling of their undisturbed sediment paths. Prior to linear modeling, multivariate analysis was again conducted by the pairwise method to identify and eliminate those independent variables that were highly correlated. The process was repeated as above for machine-caused sediment paths: canopy retention percent and maximum analysis unit slope were eliminated, while separate models were created using combined traffic area index and the

three individual types of traffic, and separate models were created using total surface roughness and the individual types of surface roughness (table 2.10).

The first model created was run for all harvest treatments and stream types, and used the number of combined sediment paths per 1,000 ft of stream as the response variable.

Independent variables included: SMZ buffer width, average slope of the analysis unit, moisture index, post harvest basal area, total surface roughness, combined traffic area index, trail density, and minimum distance from trail to stream. The model is summarized in table 2.25. The R^2 value for this model was 0.385752. Buffer width achieved significance in this model ($p=0.0081$), and was negatively correlated to number of combined sediment paths per 1,000 ft of stream, providing further support to the hypothesis that wider buffers lead to fewer sediment paths reaching the stream network. Moisture index was not significant, but was nearly so ($p=0.1109$), and was positively correlated with number of combined sediment paths per 1,000 ft of stream, continuing the pattern of higher moisture leading to increased sediment delivery. Minimum distance from trail to stream was also not significant but close ($p=0.1390$), and was negatively correlated with number of combined sediment paths per 1,000 ft of stream, meaning that as the minimum distance from trail to stream increases, the potential for sediment delivery decreases. Traffic area index was significantly negatively correlated with number of combined sediment paths ($p=0.0502$), supporting the somewhat counterintuitive idea discussed above that with an increased amount of traffic in an area, a more developed trail system with water control structures is developed, which may

actually lead to a decrease in sediment delivery because of the effectiveness of water control.

Replacing number with total width of combined sediment paths per 1,000 ft of stream and using the same set of independent variables yielded similar results (table 2.25). The R^2 value for this model was 0.317700. Buffer width was once again significantly negatively correlated with the response variable ($p=0.0015$), indicating that increased buffer width leads to a lesser total width of combined sediment paths per 1,000 ft of stream. Moisture index was not significant but close again ($p=0.1067$), and was positively related to total width of combined sediment paths per 1,000 ft of stream; higher moisture in an area leads to increased sediment delivery. Traffic area index was again significantly negatively correlated with the response variable ($p=0.0190$), supporting the idea that increased traffic in an area leads to a more fully developed trail system with effective water control, and may actually decrease sediment delivery to the stream network.

Repeating those two models, but substituting individual types of surface roughness for total surface roughness again showed similar results (table 2.26). Using number of combined sediment paths as the response variable, model R^2 was 0.453900, and again buffer width was significant and negatively correlated ($p=0.0048$). Minimum distance from trail to stream was again close to a significant negative correlation ($p=0.1009$), while combined traffic area index again showed negative correlation, though not significant ($p=0.1472$). The two most interesting results of this model had to do with surface roughness: coarse surface roughness was significantly negatively correlated with

number of combined sediment paths ($p=0.0875$), as was mixed surface roughness ($p=0.0753$). This continues the pattern discovered above for both machine-caused and undisturbed sediment paths, indicating that the larger diameter (greater than 4 inches) debris left on the ground between the skid trail and the stream helps to prevent sediment delivery. As mixed surface roughness includes both coarse and fine pieces, and fine surface roughness is not significant in any models so far, it is likely that the coarse pieces of debris are responsible for preventing sediment delivery even when the type of roughness is a mixture of fine and coarse pieces. Replacing number with width of combined sediment paths again shows that buffer width is significantly negatively correlated ($p=0.0015$), as is combined traffic area index ($p=0.0472$), though no other variables show significant correlation (table 2.26). Model R^2 was 0.342545.

Running a model using number of combined sediment paths per 1,000 ft of stream as the response variable again, but replacing combined traffic area index with individual machine type traffic area indices, and using total surface roughness again, results in further support for the main hypotheses (table 2.27). The R^2 value for this model was 0.392327. Buffer width is yet again significantly negatively correlated with the response variable ($p=0.0275$); increased buffer width leads to a decrease in the number of combined sediment paths per 1,000 ft of stream. Moisture index is positively correlated, though not significantly ($p=0.1214$). Again bulldozer traffic index is significantly negatively correlated with the response variable ($p=0.0717$), as it was in one of the models for undisturbed sediment paths, indicating that the more machine traffic in an area, the more developed the trail system and water control measures, leading to fewer

combined sediment paths. Using the same set of independent variables but replacing number with total width of combined sediment paths as the response variable continues the patterns above (table 2.27). The R^2 value for this model was 0.337005. Buffer width is significantly negatively correlated with total width of combined sediment paths ($p=0.0016$); increasing the buffer decreases sediment delivery. Moisture index is significantly positively correlated with total width of combined sediment paths ($p=0.0861$); increased moisture in an area correlates with increased sediment delivery. Traffic indices for the feller-buncher ($p=0.1053$) and bulldozer ($p=0.1109$), though not significant, continue the pattern of negative correlation with sediment delivery.

Repeating the last two models but substituting individual types of surface roughness for total surface roughness supports the main patterns again (table 2.28). For number of combined sediment paths, model R^2 was 0.463118, with buffer width significantly negatively correlated ($p=0.0250$), as well as coarse surface roughness ($p=0.0757$). For width of combined sediment paths, model R^2 was 0.354466, with buffer width once again significantly negatively correlated ($p=0.0020$).

II.3.v. Relationship between machine-caused and undisturbed overland sediment delivery pathways

One final question worth asking about overland sediment delivery paths is the relative frequency of machine-caused paths in a forest harvest setting, as opposed to sediment paths that are not visibly associated with harvest machine activity. Answering this question should give some insight into whether forest management activities constitute a

major or minor source of sediment delivery. In order to answer this question, matched pairs analysis was conducted to compare the number and width of machine-caused sediment paths to the number and width of undisturbed sediment paths, by SMZ type (ephemeral, intermittent, and perennial). This analysis was done using only the three harvested treatment watersheds, as the control watersheds by definition had no machine-caused sediment paths.

Comparing the mean number of undisturbed sediment paths per 1,000 ft of stream to the mean number of machine-caused sediment paths per 1,000 ft of stream showed that the mean number of undisturbed sediment paths per 1,000 ft of stream was significantly higher in the ephemeral analysis units ($p=0.0115$) and the intermittent analysis units ($p=0.0791$), but not in the perennial analysis units ($p=0.4367$) (table 2.29). Similarly, comparing the mean total width of undisturbed sediment paths per 1,000 ft of stream to the mean total width of machine-caused sediment paths per 1,000 ft of stream showed that the mean total width of undisturbed sediment paths per 1,000 ft of stream was significantly higher in the ephemeral analysis units ($p=0.0866$) and the intermittent analysis units ($p=0.0363$), but not in the perennial analysis units ($p=0.6794$) (table 2.29). Though the perennial analysis units did not show the same pattern, the significantly greater number and width of undisturbed sediment paths opposed to those caused by harvest machines in both the ephemeral and intermittent SMZs gives at least some evidence that harvesting machine-induced sediment delivery is less important than that which originates from areas not visibly disturbed by harvest machine activity. As discussed above, this conclusion does not necessarily mean that the greater number of

sediment paths coming from undisturbed areas of forest floor has nothing to do with harvesting activity, only that the activity of harvest machines disturbing the forest floor is not involved.

One may wonder as well if there is a correlation between machine-caused and undisturbed sediment paths, such that if the number or width of one type increases in an area, the other decreases. In order to test for this possibility, linear regressions were performed with data from the harvested watersheds, as there are no machine-caused sediment paths in the control watersheds. No relationship was observed between the number of machine-caused and the number of undisturbed sediment paths per 1,000 ft of stream ($R^2=0.0177$; figure 2.20), nor between the total width of machine-caused and the total width of undisturbed sediment paths per 1,000 ft of stream ($R^2=0.0101$; figure 2.21).

II.4. Summary of sediment path study

The results of this study should be useful in understanding the dynamics and spatial distribution of overland sediment delivery mechanisms during forest management. In particular, it is interesting to note that all of the machine-caused sediment paths observed in this study originated from a skid trail, rather than from the general harvest area. In a study by Rivenbark and Jackson (2004), only 25% of the SMZ breakthroughs they observed were caused by drainage from the trail network, whereas Litschert and MacDonald (2009) found that 5 of 6 pathways (83%) originated from the trail network. This study found that 100% of sediment paths were associated with water control structures, which is in close agreement to Litschert and MacDonald (2009). In fact, these

structures may have actually concentrated the flow and increased the likelihood of sediment reaching the stream network, as found by Lakel et al. as well (2010). The finding of this study that placing water control structures at low points along the skid trail system leads to a greatly increased chance of initiating overland sediment delivery pathways that reach the stream is important, and should be considered when implementing retirement BMPs on skid trails.

A study of sediment transport from newly constructed graveled forest roads done at the Coweeta Hydrologic Laboratory found that land slope was the most important predictor of sediment transport distance (Swift 1986). To the contrary, this study did not find much evidence of a relationship between slope of the hillside and sediment transport distance from source to stream. However, a major difference between the Coweeta study and this one is that the Coweeta study looked at sediment transport distance of all sediment paths, whether or not they actually reached the stream network, while the present study documented only those sediment paths that did reach the stream. If this study had documented all sediment paths in the watersheds, then a relationship between hillslope and sediment transport distance may have been observed here as well. The focus here on only those sediment paths that actually reached the stream system means that those paths may have been able to travel much farther downhill given their volume and velocity, but they reached a stream before they could have been dispersed on the forest floor. Also, in this study, the general lack of variability in slope steepness and morphology between the skid trails and the streams may not have provided the variability needed to adequately determine the effect of slope degree on sediment path transport distance. This lack of

variability in the character of the slopes may also help to explain why analysis unit slope only showed significance in one model, for undisturbed sediment paths in the control watersheds.

The issue of buffer width and canopy retention within that buffer as means to reduce overland sediment delivery was a major focus of the present study, and analyzing the current Kentucky SMZ requirements was a stated objective. Where Lakel et al. (2010) found that wider SMZ buffers were no more effective in preventing overland sediment delivery than narrower buffers, Swift (1986) found to the contrary that wider SMZ buffers were effective at preventing a greater proportion of sediment delivery to streams than narrower buffers. This study confirms Swift's findings at Coweeta, providing evidence that the presence of an SMZ buffer minimized the number and width of sediment paths on ephemeral channels, increased buffer width and canopy retention helped prevent sediment paths in the intermittent channels, and greater buffer width helped prevent machine-caused sediment paths in perennial channels. Linear modeling also showed that buffer width was significantly negatively related to the number and width of undisturbed sediment paths, as well as the number and width of combined machine-caused and undisturbed sediment paths.

Moisture index, a function of the aspect of a site, showed a significant positive relationship in this study to number and width of machine-caused sediment paths, the width of undisturbed sediment paths, as well as to the width of combined machine-caused and undisturbed sediment paths. A similar finding is reported by Litschert and

MacDonald (2009), where the length of overland flow pathways was significantly related to the cosine of the aspect of the hillside.

Litschert and MacDonald (2009) reported that surface roughness had a negative effect on the ability of an overland sediment pathway to reach the stream network, while Swift (1986) also found that a brush barrier below the road network reduced sediment transport distances to half that of those without a brush barrier, and that SMZ widths could be reduced where brush barriers are used. The findings of this study confirm that total surface roughness is significantly negatively related to the number and width of machine-caused sediment paths. Further, coarse surface roughness (those pieces greater than 4 inches in diameter) is significantly negatively related to the number of undisturbed sediment paths, and the number of combined machine-caused and undisturbed sediment paths. The greater coarse surface roughness in the 55ft-50% perennial stream analysis units as compared to the 55ft-100% perennial stream analysis units may explain the greater number and width of machine-caused sediment paths in the 55ft-100% treatment even though the buffer widths of both treatments are the same. It seems that less canopy retention and more harvesting within the perennial SMZ buffer in the 55ft-50% treatment resulted in greater coarse surface roughness, which in turn led to a reduction in perennial stream sediment delivery between that treatment and the 55ft-100% treatment.

The present study found that as the minimum distance from the trail to the stream network in an analysis unit increased, the number and width of machine-caused sediment paths decreased. The idea that ground disturbance near the stream network increases the

likelihood for sediment delivery is also supported by Rashin et al. (2006), who found that ground disturbance within 10 meters of the stream is more likely than not to deliver sediment to the stream.

This study found evidence that tracked forest harvesting equipment such as bulldozers and feller-bunchers may increase the potential for overland sediment delivery to the stream network, while wheeled equipment such as log skidders may decrease it. A plausible explanation for this state of affairs is that the tracks of the bulldozers and feller-bunchers leave more loosely attached soil available to be dislodged by rainfall and flow downslope with runoff because of the churning action of the tracks, while skidder tires compact the soil more than churn it up, and help to decrease the amount of loosely attached soil available to flow downslope. Another interesting finding by this study is that an increase in the trail network and the amount of traffic in an area may actually help to decrease the potential for sediment paths to enter the stream network, presumably because of the addition of effective water control structures and their ability to reduce the velocity and volume of these overland sediment flows before they reach the streams. Unharvested areas do not have these water control structures, and sediment paths that do get started in these areas may be able to gain enough velocity and volume to reach the stream.

Finally, it is intriguing that this study's results suggest that overland sediment delivery from areas not visibly disturbed by the activity of harvest machines may be more of a factor in stream sedimentation than that caused by the activity of those machines. The

significantly greater number and width of the undisturbed sediment paths in the ephemeral and intermittent stream sections, though not in the perennial sections, supports this contention. A study by Terrell (2008) showed that natural concentrated overland flow paths entered the SMZ and the stream system in their treatment watersheds before harvest operations commenced. However, more detailed investigation of the actual volume of sediment delivered by these flows from undisturbed areas as opposed to those caused by machine traffic would have to be undertaken to confirm this theory. Anecdotal observation suggests that the sediment paths resulting from undisturbed areas may be delivering a much lower volume of sediment than those flows originating from areas of forest floor disturbed by harvest machine activity, even though there may be a greater total number and width of the paths from undisturbed areas. Obtaining a measure of sediment volume delivered by each path would be necessary for a full investigation of this hypothesis, rather than the proxy of sediment path width used in this study.

Table 2.1—Treatments used for Robinson Forest Streamside Management Zone project.

Treatment number	Treatment name	Stream type	SMZ Width	Canopy Cover Retained
		perennial		
0	Control	intermittent	control; no treatment	
		ephemeral		
		perennial	normal (55ft)	normal (50%)
1	55ft-50%	intermittent	normal (25ft)	normal (0%)
		ephemeral	normal ephemeral width (0ft) ²	normal (0%)
		perennial	2 x normal (110ft)	2 x normal (100%)
2	110ft-100%	intermittent	2 x normal (50ft)	2 x normal (25%)
		ephemeral	normal intermittent width (25ft) ¹	2 x normal (bank trees)
		perennial	normal (55ft)	2 x normal (100%)
3	55ft-100%	intermittent	normal (25ft)	2 x normal (25%)
		ephemeral	normal ephemeral width (0ft) ¹	2 x normal (bank trees)

¹Improved stream crossings.

²No improved stream crossings.

Table 2.2—Summary table of the Robinson Forest Streamside Management Zone Project.

Unit	Treatment	Acres	BF Doyle grade logs removed (BF/acre)	Tons pulp and chip removed (tons/acre)	Harvest operator	Mobile harvest equipment used
Falling Rock	Control	240	--	--	--	--
Little Millseat	Control	193	--	--	--	--
North Shelly Rock	55ft-50%	67	368,084 (5494)	2664.2 (39.8)	Logger 1	Timbco 445EXL feller- buncher; John Deere 650, 700, and 850 dozers; CAT 525 and 545 skidders
West Shelly Rock	110ft- 100%	157	805,186 (5129)	4283.0 (27.3)		
South Shelly Rock	55ft-100%	81	262,180 (3238)	4073.6 (50.3)		
Booker Fork	55ft-50%	145	508,887 (3510)	1342.0 (9.3)	Logger 2	Timbco 445 feller- buncher; 3 John Deere 650 dozers, John Deere 540 and 648 skidders
Wet Fork	110ft- 100%	277	945,173 (3412)	4490.5 (16.2)		
Goff Hollow	55ft-100%	93	249,326 (2681)	407.5 (4.4)		
Totals			3,138,836	17,260.81		

Table 2.2 continued—Summary table of the Robinson Forest Streamside Management Zone Project.

Unit	Residual basal area (BF/acre)	Total length of skid trails (ft)	Approx. acres of skid trails	Total acres of landings	Number of water control structures
Falling Rock	**	--	--	--	--
Little Millseat	148	--	--	--	--
North Shelly Rock	33	21,862	8.0	2.6	367
West Shelly Rock	57	51,133	18.8		851
South Shelly Rock	64	25,301	9.3		435
Booker Fork	**	35,576	13.1	**	**
Wet Fork	**	77,772	28.6	**	**
Goff Hollow	**	30,946	11.4	**	358
Totals				**=incomplete data	

Table 2.3—Categories used to document observed skid trail traffic intensity (after Michels 2009).

Trail designation	Observed characteristics
Primary skid trail	Bare mineral soil w/ much residual damage – litter layer completely removed down to bare mineral soil (bladed trail), turn trees, other residual trees, and stumps in or near trail severely damaged (most of the bark has been knocked off)
Secondary skid trail	Bare mineral soil w/ minimal residual damage – litter layer completely removed down to bare mineral soil (most likely bladed), turn trees, other residual trees, and stumps in or near trail not very damaged (most of the bark is still left)
Tertiary skid trail	Compressed, no bare mineral soil – litter layer has been disturbed, but some organic material still remains – nonbladed

Table 2.4—Categories used to document woody debris on the ground surface, with the value given to each.

Observed on ground surface	Diameter	Value
Fine branch slash on ground surface	Less than or equal to 4 inches	1
Coarse branch slash on ground surface	Greater than 4 inches	1
Mixture of fine and coarse branch slash on ground surface		1

Table 2.5—Number and type of analysis units in each of the harvest and control watersheds.

Watershed	Treatment	Ephemeral analysis units	Intermittent analysis units	Perennial analysis units	Total
North Shelly Rock	55ft-50%	3	3	3	9
West Shelly Rock	110ft- 100%	10	10	4	24
South Shelly Rock	55ft- 100%	3	4	4	11
Little Millseat	Control	3	6	4	13
Falling Rock	Control	10	6	4	20
All					77

Table 2.6—Actual number of sediment paths documented in each treatment watershed, by stream type at which the paths terminated. These figures are not adjusted for stream section length.

	Machine-caused sediment paths							Undisturbed sediment paths										
Treatment	Ephemeral	Within analysis unit	Intermittent	Within analysis unit	Perennial	Within analysis unit	Total	Total within analysis unit	Ephemeral	Within analysis unit	Intermittent	Within analysis unit	Perennial	Within analysis unit	Total	Total within analysis unit	Total sediment paths	Total within analysis unit
Control (Little Millseat)	0	0	0	0	0	0	0	0	53	7	64	36	49	24	166	67	166	67
Control (Falling Rock)	0	0	0	0	0	0	0	0	155	87	52	32	27	22	234	141	234	141
55ft-50%	11	5	12	10	0	0	23	15	28	8	9	5	8	8	45	21	68	36
110ft-100%	7	5	9	9	1	1	17	15	28	13	31	23	20	9	79	45	96	60
55ft-100%	11	1	6	5	15	14	32	20	21	12	22	22	3	3	46	37	78	57
All	29	11	27	24	16	15	72	50	285	127	178	118	107	66	570	311	642	361

Table 2.7—Water control structures documented within analysis units of the three harvested watersheds, by the morphology of the skid trail where they were constructed. Percentage of water control structures associated with initiation of machine-caused sediment paths is also shown.

Skid trail morphology	Reverse grade structures		Berm cuts	
	Total	Producing sediment path (%)	Total	Producing sediment path
Flat	155	13 (8.3%)	**	1
Low point	12	10 (83.3%)	**	2
Sloping	312	45 (14.4%)	**	1
Total	479	68 (14.2%)	**	4

**=unknown

Table 2.8.—Mean number and mean total width of machine-caused sediment paths per 1,000 ft of stream, by treatment and stream type. Values with the same letter are not significantly different within stream type.

Treatment	Ephemeral		Intermittent		Perennial	
	Mean #	Mean total width (ft)	Mean #	Mean total width (ft)	Mean #	Mean total width (ft)
55ft-50%	3.2a	25.2a	10.0a	61.1a	0.0b	0.0b
110ft-100%	1.2a	10.1a	1.5b	8.5b	0.4b	0.9b
55ft-100%	0.8a	4.0a	3.5ab	36.1ab	6.9a	57.7a

Table 2.9—Mean coarse surface roughness values by treatment and stream type. Values with the same letter are not significantly different within stream type.

	Ephemeral	Intermittent	Perennial
Treatment	Mean surface roughness value	Mean surface roughness value	Mean surface roughness value
55ft-50%	0.170a	0.070a	0.084a
110ft-100%	0.098ab	0.040a	0.025b
55ft-100%	0.027bc	0.063a	0.013b

Table 2.10—Results of pairwise multivariate analyses among independent variables used for modeling.

Harvested watersheds			
Independent variable	Correlated with	Value	Variable eliminated from modeling
Buffer width	Canopy retention percent	0.8179	Canopy percent
Maximum analysis unit slope	Average analysis unit slope	0.7623	Maximum slope
Total surface roughness	Fine branch surface roughness	0.7804	Keep both variables, but run separate models
Total traffic area index	Skidder traffic area index	0.7119	Keep both variables, but run separate models
Total traffic area index	Bulldozer traffic area index	0.7920	Keep both variables, but run separate models
Control watersheds			
Total surface roughness	Fine branch surface roughness	0.9394	Keep both variables, but run separate models

Table 2.11—Summary table of linear models for harvested watersheds, using number and total width of machine-caused sediment paths per 1,000 ft of stream as the response variables, with combined traffic area index and total surface roughness.

Response variable	Independent variable	p value	Sign of relationship to response variable
Number of sediment paths	Moisture index	0.0459	+
	Total surface roughness	0.0606	-
	Minimum distance from trail to stream	0.0947	-
Total width of sediment paths	Moisture index	0.0441	+
	Total surface roughness	0.0609	-
	Minimum distance from trail to stream	0.0184	-

Table 2.12—Summary table of linear models for harvested watersheds, using number and total width of machine-caused sediment paths per 1,000 ft of stream as the response variables, with individual machine type traffic area indices and total surface roughness.

Response variable	Independent variable	p value	Sign of relationship to response variable
Number of sediment paths	Moisture index	0.1154	+
	Total surface roughness	0.0837	-
	Minimum distance from trail to stream	0.1080	-
	Feller-buncher traffic area index	0.1335	+
Total width of sediment paths	Moisture index	0.1153	+
	Total surface roughness	0.0824	-
	Minimum distance from trail to stream	0.0204	-
	Feller-buncher traffic area index	0.2135	+
	Skidder traffic area index	0.1308	-

Table 2.13—Summary table of linear models for harvested watersheds, using number and total width of machine-caused sediment paths per 1,000 ft of stream as the response variables, with combined traffic area index and individual types of surface roughness.

Response variable	Independent variable	p value	Sign of relationship to response variable
Number of sediment paths	Moisture index	0.0790	+
	Minimum distance from trail to stream	0.0810	-
	Coarse surface roughness	0.1325	-
Total width of sediment paths	Moisture index	0.0626	+
	Minimum distance from trail to stream	0.0275	-

Table 2.14—Summary table of linear models for harvested watersheds, using number and total width of machine-caused sediment paths per 1,000 ft of stream as the response variables, with individual traffic area index and individual types of surface roughness.

Response variable	Independent variable	p value	Sign of relationship to response variable
Number of sediment paths	Minimum distance from trail to stream	0.0827	-
	Coarse surface roughness	0.1011	-
	Feller-buncher traffic area index	0.0866	+
Total width of sediment paths	Minimum distance from trail to stream	0.0242	-
	Feller-buncher traffic area index	0.1496	+
	Skidder traffic area index	0.1469	-

Table 2.15—Mean number and mean total width of undisturbed sediment paths per 1,000 ft of stream, by control watershed and stream type. Values with the same letter are not significantly different within stream type.

Treatment	Ephemeral		Intermittent		Perennial	
	Mean #	Mean total width (ft)	Mean #	Mean total width (ft)	Mean #	Mean total width (ft)
Control (Little Millseat)	7.7a	93.7a	16.6a	173.9a	7.6a	21.0a
Control (Falling Rock)	15.3a	86.8a	8.8a	60.6b	8.4a	47.7a

Table 2.16—Mean number and mean total width of undisturbed sediment paths per 1,000 ft of stream, by treatment and stream type. Values with the same letter are not significantly different within stream type.

Treatment	Ephemeral		Intermittent		Perennial	
	Mean #	Mean total width (ft)	Mean #	Mean total width (ft)	Mean #	Mean total width (ft)
Control	13.6a	88.4a	12.7a	117.3a	8.0a	34.4a
55ft-50%	9.0ab	125.2a	6.0ab	20.8a	5.4ab	32.3a
110ft-100%	3.3b	18.1a	3.7b	40.4a	2.8b	10.7a
55ft-100%	10.3ab	49.4a	13.6a	126.2a	1.2b	4.9a

Table 2.17—Summary table of linear models for control watersheds only, using number and total width of undisturbed sediment paths per 1,000 ft of stream as the response variables, with individual types of surface roughness.

Response variable	Independent variable	p value	Sign of relationship to response variable
Number of sediment paths	Average slope	0.0782	+
	Coarse surface roughness	0.0473	-
Total width of sediment paths	None		

Table 2.18—Summary table of linear models for Falling Rock control watershed only, using number and total width of undisturbed sediment paths per 1,000 ft of stream as the response variables.

Type of surface roughness in model	Response variable	Independent variable	p value	Sign of relationship to response variable
Total	Number of sediment paths	None		
	Total width of sediment paths	Moisture index	0.0682	+
Individual	Number of sediment paths	None		
	Total width of sediment paths	None		

Table 2.19—Summary table of linear models for Little Millseat control watershed only, using number and total width of undisturbed sediment paths per 1,000 ft of stream as the response variables.

Type of surface roughness in model	Response variable	Independent variable	p value	Sign of relationship to response variable
Total	Number of sediment paths	None		
	Total width of sediment paths	Trail density	0.0875	+
Individual	Number of sediment paths	Average basal area	0.0922	+
	Total width of sediment paths	Trail density	0.0908	+

Table 2.20—Summary table of linear models for harvested watersheds, using number and total width of undisturbed sediment paths per 1,000 ft of stream as the response variables, with combined traffic area index and total surface roughness.

Response variable	Independent variable	p value	Sign of relationship to response variable
Number of sediment paths	SMZ buffer width	0.0059	-
	Traffic area index	0.0431	-
Total width of sediment paths	SMZ buffer width	0.0041	-
	Traffic area index	0.0498	-

Table 2.21—Summary table of linear models for harvested watersheds, using number and total width of undisturbed sediment paths per 1,000 ft of stream as the response variables, with combined traffic area index and individual surface roughness.

Response variable	Independent variable	p value	Sign of relationship to response variable
Number of sediment paths	SMZ buffer width	0.0043	-
	Traffic area index	0.1269	-
Total width of sediment paths	SMZ buffer width	0.0040	-
	Traffic area index	0.0981	-

Table 2.22—Summary table of linear models for harvested watersheds, using number and total width of undisturbed sediment paths per 1,000 ft of stream as the response variables, with individual machine type traffic area indices and total surface roughness.

Response variable	Independent variable	p value	Sign of relationship to response variable
Number of sediment paths	SMZ buffer width	0.0084	-
	Feller-buncher traffic area index	0.0704	-
	Bulldozer traffic area index	0.0369	-
Total width of sediment paths	SMZ buffer width	0.0018	-
	Feller-buncher traffic area index	0.0298	-
	Bulldozer traffic area index	0.1412	-

Table 2.23—Summary table of linear models for harvested watersheds, using number and total width of undisturbed sediment paths per 1,000 ft of stream as the response variables, with individual machine type traffic area indices and individual surface roughness.

Response variable	Independent variable	p value	Sign of relationship to response variable
Number of sediment paths	SMZ buffer width	0.0085	-
	Feller-buncher traffic area index	0.1842	-
	Bulldozer traffic area index	0.1109	-
Total width of sediment paths	SMZ buffer width	0.0024	-
	Feller-buncher traffic area index	0.0603	-
	Bulldozer traffic area index	0.2321	-

Table 2.24—Mean number and mean total width of combined machine-caused and undisturbed sediment paths per 1,000 ft of stream, by treatment and stream type. Values with the same letter are not significantly different within stream type.

Treatment	Ephemeral		Intermittent		Perennial	
	Mean #	Mean total width (ft)	Mean #	Mean total width (ft)	Mean #	Mean total width (ft)
55ft-50%	12.2a	150.4a	16.0a	82.0ab	5.4a	32.3a
110ft-100%	4.5b	28.2b	5.2b	49.0b	3.2a	11.6a
55ft-100%	11.1a	53.5ab	17.1a	162.3a	8.1a	62.6a

Table 2.25—Summary table of linear models for harvested watersheds, using number and total width of combined machine-caused and undisturbed sediment paths per 1,000 ft of stream as the response variables, with combined traffic area index and total surface roughness.

Response variable	Independent variable	p value	Sign of relationship to response variable
Number of sediment paths	SMZ buffer width	0.0081	-
	Moisture index	0.1109	+
	Traffic area index	0.0502	-
	Minimum distance from trail to stream	0.1390	-
Total width of sediment paths	SMZ buffer width	0.0015	-
	Traffic area index	0.0190	-
	Moisture index	0.1067	+

Table 2.26—Summary table of linear models for harvested watersheds, using number and total width of combined machine-caused and undisturbed sediment paths per 1,000 ft of stream as the response variables, with combined traffic area index and individual surface roughness.

Response variable	Independent variable	p value	Sign of relationship to response variable
Number of sediment paths	SMZ buffer width	0.0048	-
	Traffic area index	0.1472	-
	Minimum distance from trail to stream	0.1009	-
	Coarse surface roughness	0.0875	-
	Mixed surface roughness	0.0753	-
Total width of sediment paths	SMZ buffer width	0.0015	-
	Traffic area index	0.0472	-

Table 2.27—Summary table of linear models for harvested watersheds, using number and total width of combined machine-caused and undisturbed sediment paths per 1,000 ft of stream as the response variables, with individual machine type traffic area indices and total surface roughness.

Response variable	Independent variable	p value	Sign of relationship to response variable
Number of sediment paths	SMZ buffer width	0.0275	-
	Moisture index	0.1214	+
	Bulldozer traffic area index	0.0717	-
Total width of sediment paths	SMZ buffer width	0.0016	-
	Moisture index	0.0861	+
	Bulldozer traffic area index	0.1109	-
	Feller-buncher traffic area index	0.1053	-

Table 2.28—Summary table of linear models for harvested watersheds, using number and total width of combined machine-caused and undisturbed sediment paths per 1,000 ft of stream as the response variables, with individual machine type traffic area indices and individual surface roughness.

Response variable	Independent variable	p value	Sign of relationship to response variable
Number of sediment paths	SMZ buffer width	0.0250	-
	Coarse surface roughness	0.0757	-
Total width of sediment paths	SMZ buffer width	0.0020	-

Table 2.29—Mean number and mean total width of machine-caused and undisturbed sediment paths per 1,000 ft of stream by stream type, harvested watersheds only. Values with the same letter are not significantly different within stream type.

	Ephemeral		Intermittent		Perennial	
	Mean #	Mean total width (ft)	Mean #	Mean total width (ft)	Mean #	Mean total width (ft)
Machine-caused	1.5a	11.8a	3.5a	24.3a	2.6a	21.3a
Undisturbed	5.7b	44.1b	6.4b	57.2b	2.9a	14.5a

Figure 2.1—Map showing the location of Robinson Forest within Kentucky. Fayette County is in blue; Breathitt, Knott, and Perry Counties are in green. Robinson Forest is the collection of black-shaded areas inside the orange circle.

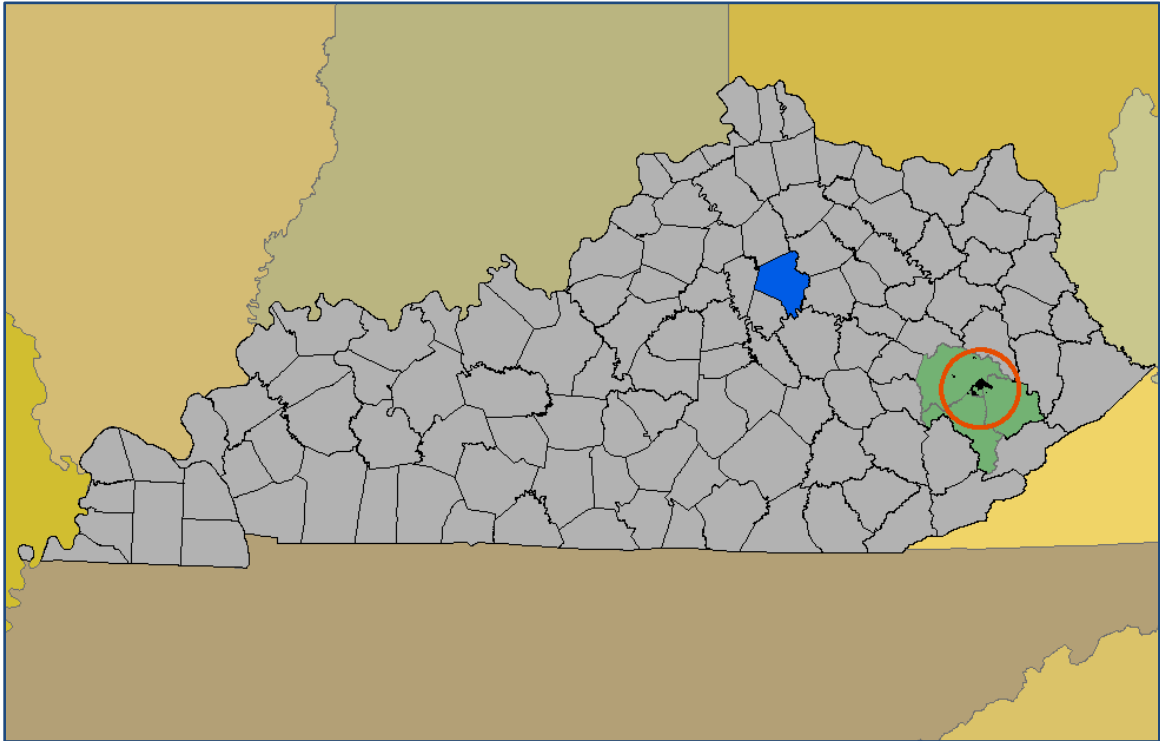


Figure 2.2—Map showing the location of the SMZ project treatments. Area within the green outline is the main tract of Robinson Forest. Green, blue and red shaded areas represent watersheds harvested during the project, while yellow shaded areas represent unharvested controls.

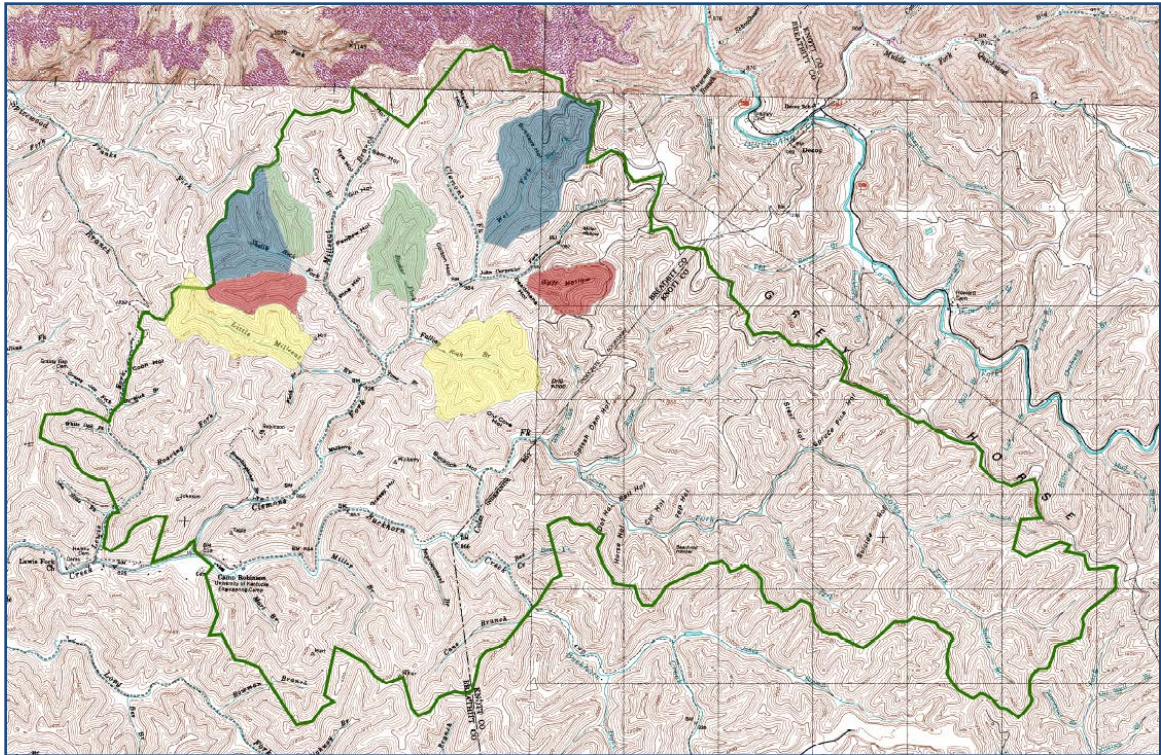


Figure 2.3—Map of the 55ft-100% treatment watershed in green, showing units subjected to experimental analysis in orange. Perennial stream sections are in solid blue, intermittent sections are in dashed blue, and ephemeral stream sections are in hatched blue. The skid trail network is represented by black lines. The log landing area is at the high point at the northwest of the watershed, and is represented in gray.

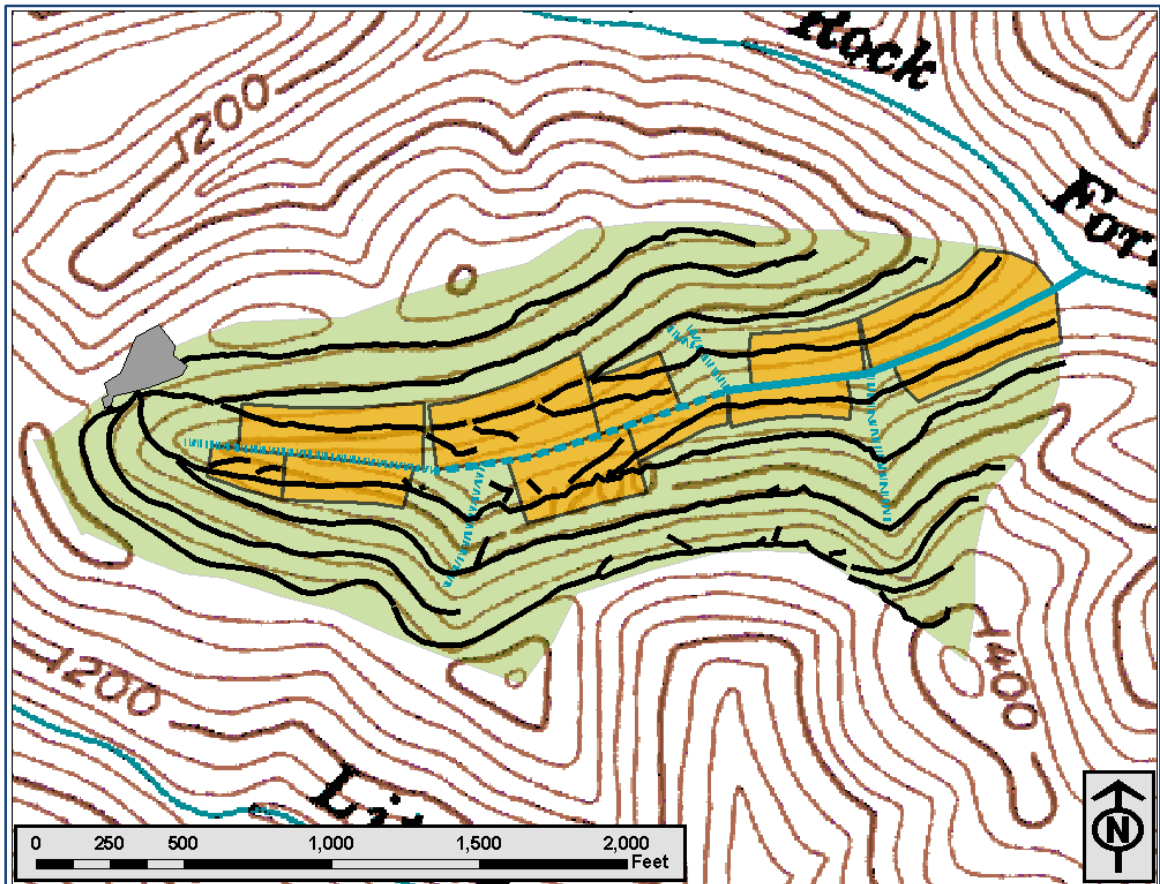


Figure 2.4—Map of an analysis unit in the 55ft-100% treatment watershed. Watershed is in green, and the analysis unit is in orange. The section of perennial stream is in solid blue. The skid trail network is represented by black lines. Green triangles represent documented sediment paths coming into the stream from the south, while red triangles represent those coming in from the north.

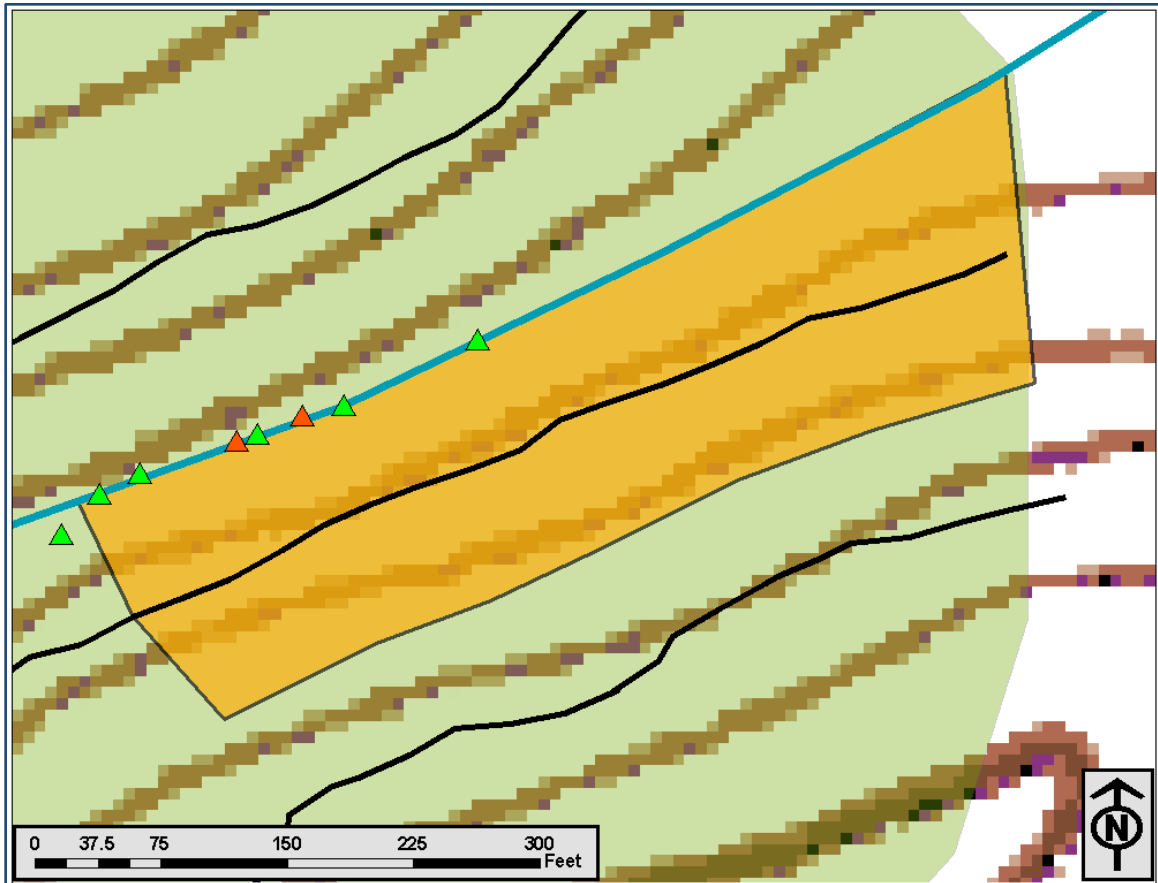


Figure 2.5—Map of 9 analysis units (3 ephemeral, 3 intermittent, 3 perennial) in the 55ft-50% treatment watershed North Shelly Rock. Analysis units are in hatched orange, skid trail network is in black, perennial stream sections are solid blue lines, intermittent stream sections are dashed blue lines, and ephemeral stream sections are hatched blue lines.

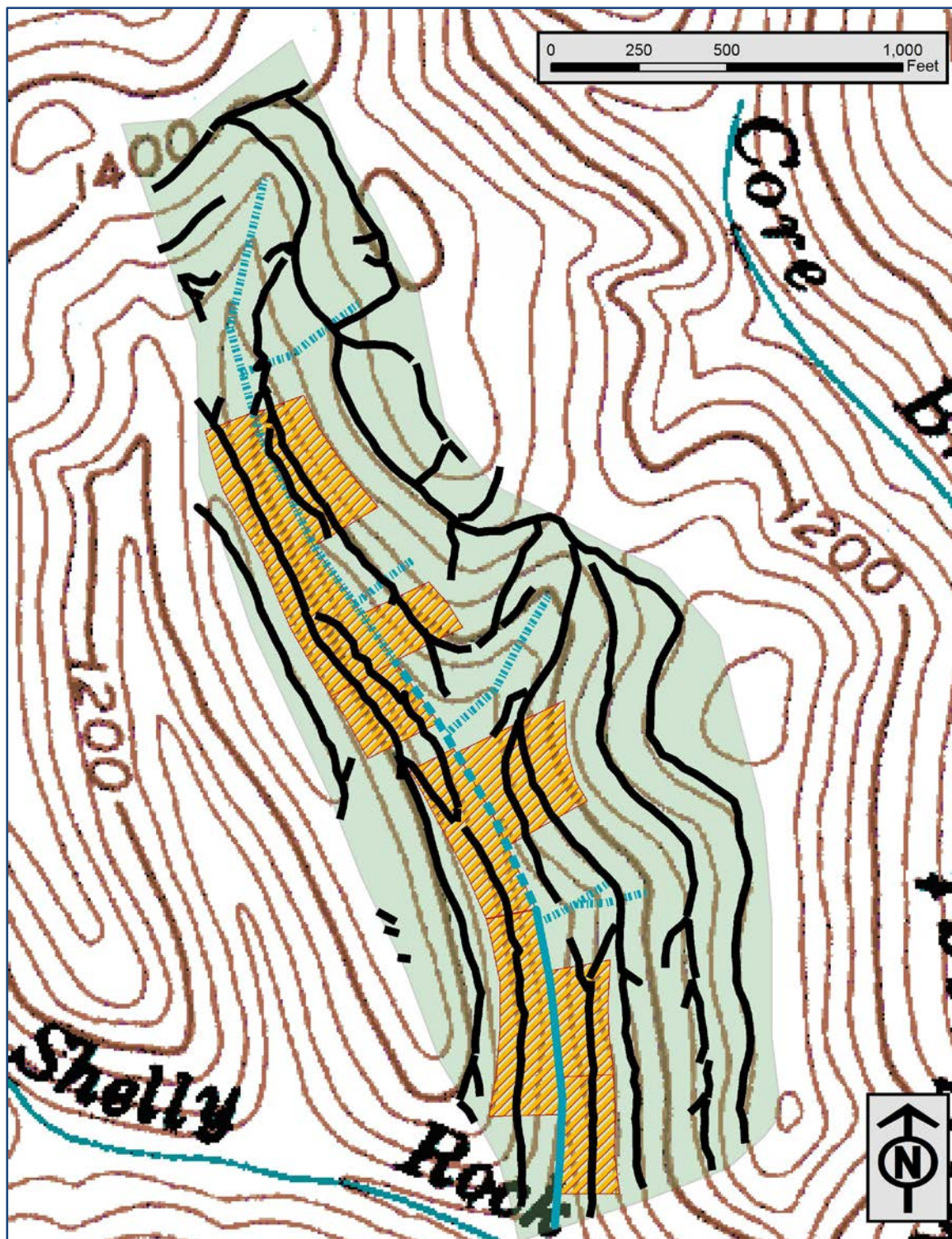


Figure 2.6—Map of 24 analysis units (10 ephemeral, 10 intermittent, 4 perennial) in the 110ft-100% treatment watershed West Shelly Rock. Analysis units are in hatched orange, skid trail network is in black, perennial stream sections are solid blue lines, intermittent stream sections are dashed blue lines, and ephemeral stream sections are hatched blue lines.

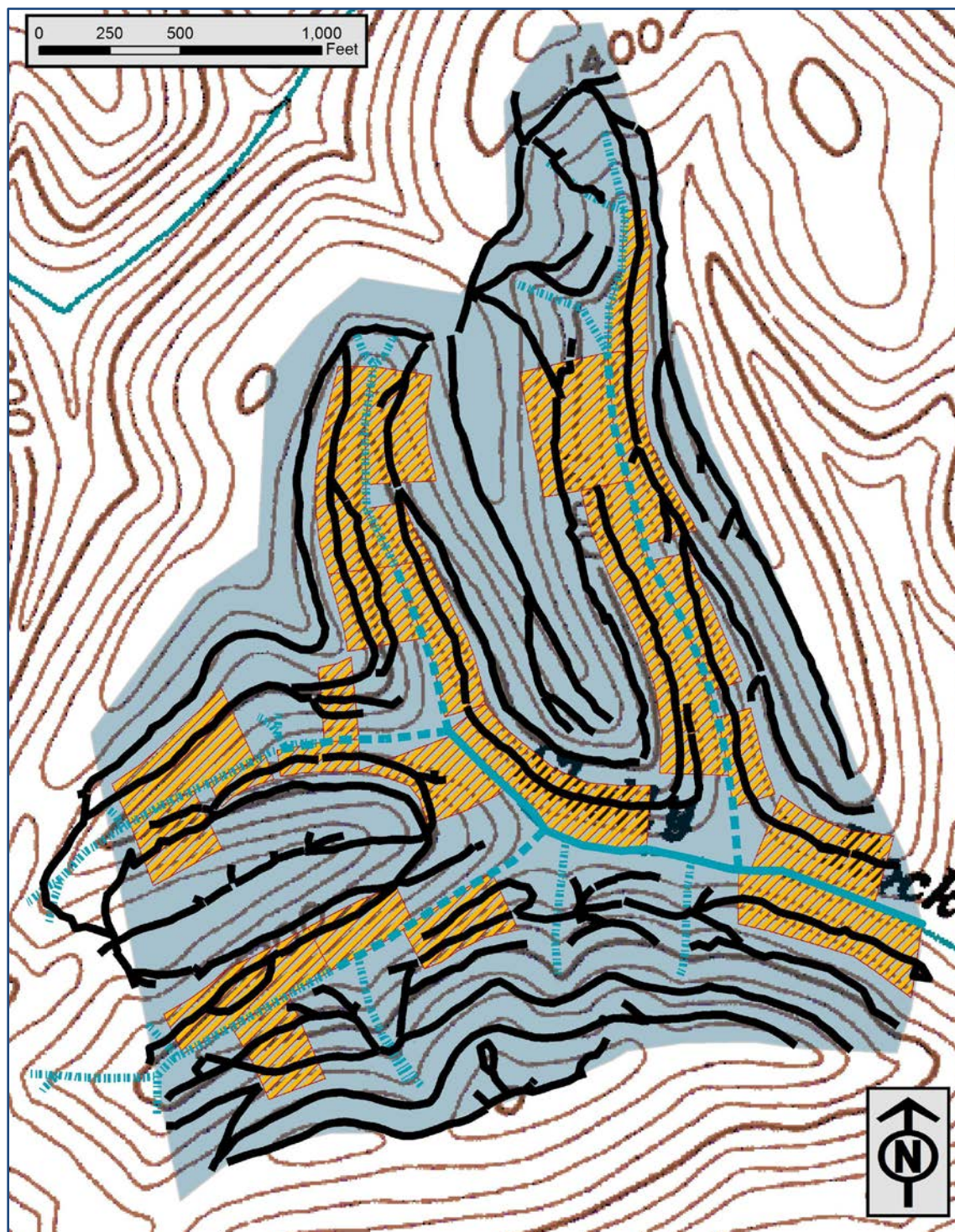


Figure 2.7—Map of 11 analysis units (3 ephemeral, 4 intermittent, 4 perennial) in the 55ft-100% treatment watershed South Shelly Rock. Analysis units are in hatched orange, skid trail network is in black, perennial stream sections are solid blue lines, intermittent stream sections are dashed blue lines, and ephemeral stream sections are hatched blue lines.

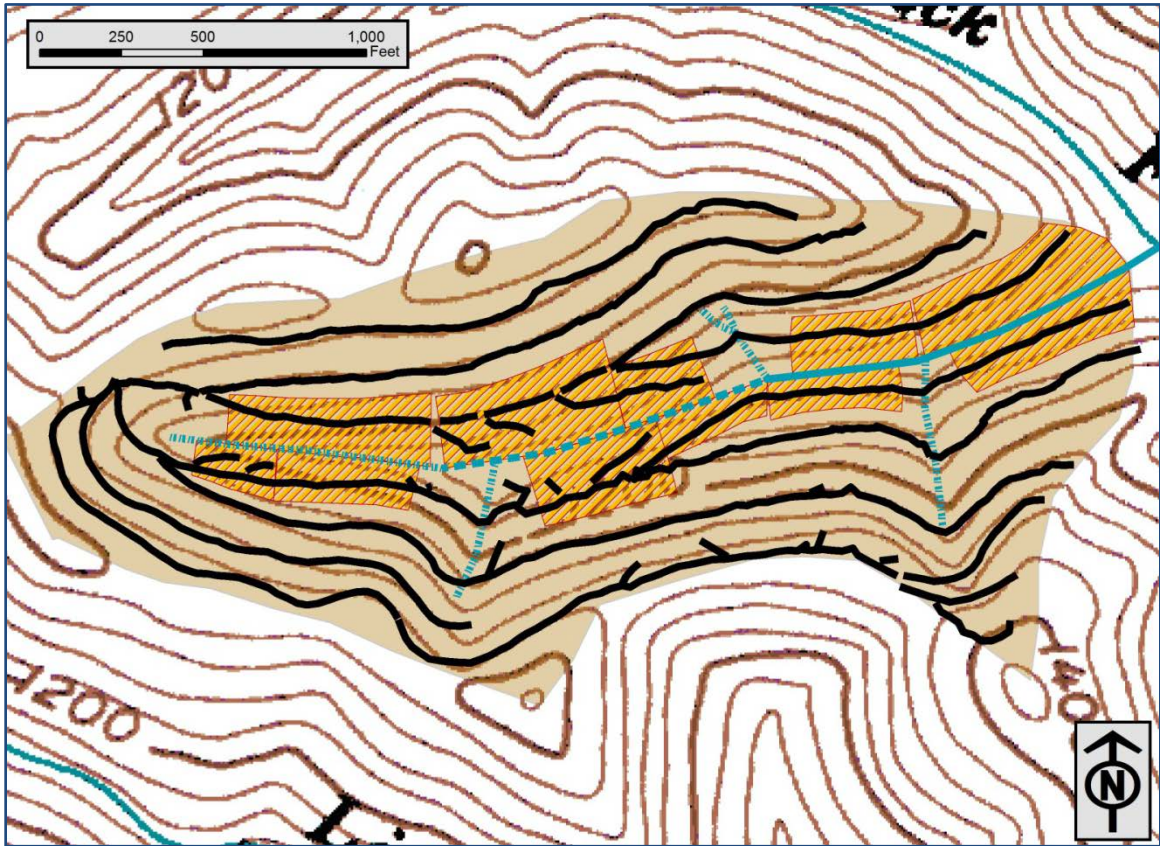


Figure 2.8—Map of 13 analysis units (3 ephemeral, 6 intermittent, 4 perennial) in control watershed Little Millseat. Analysis units are in hatched orange, skid trail network is in black, perennial stream sections are solid blue lines, intermittent stream sections are dashed blue lines, and ephemeral stream sections are hatched blue lines.

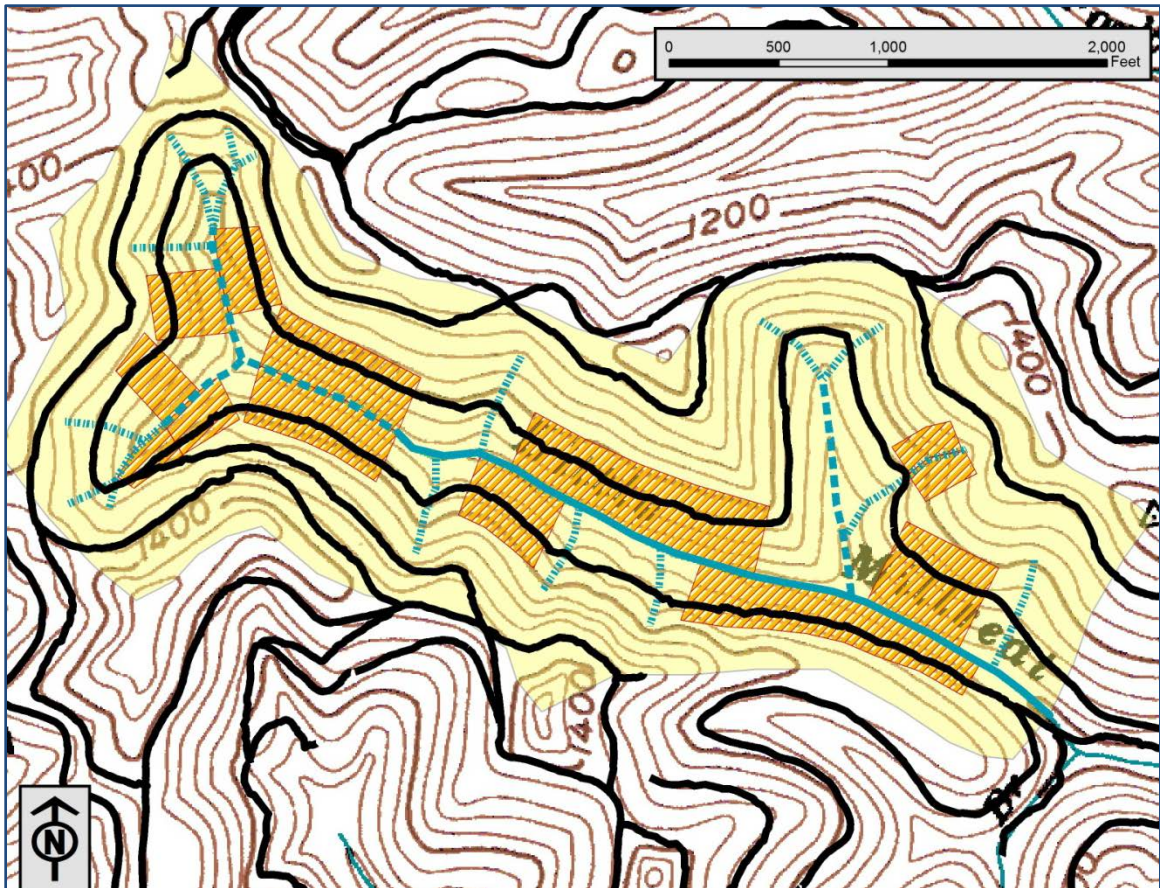


Figure 2.9—Map of 20 analysis units (10 ephemeral, 6 intermittent, 4 perennial) in control watershed Falling Rock. Analysis units are in hatched orange, skid trail network is in black, perennial stream sections are solid blue lines, intermittent stream sections are dashed blue lines, and ephemeral stream sections are hatched blue lines.

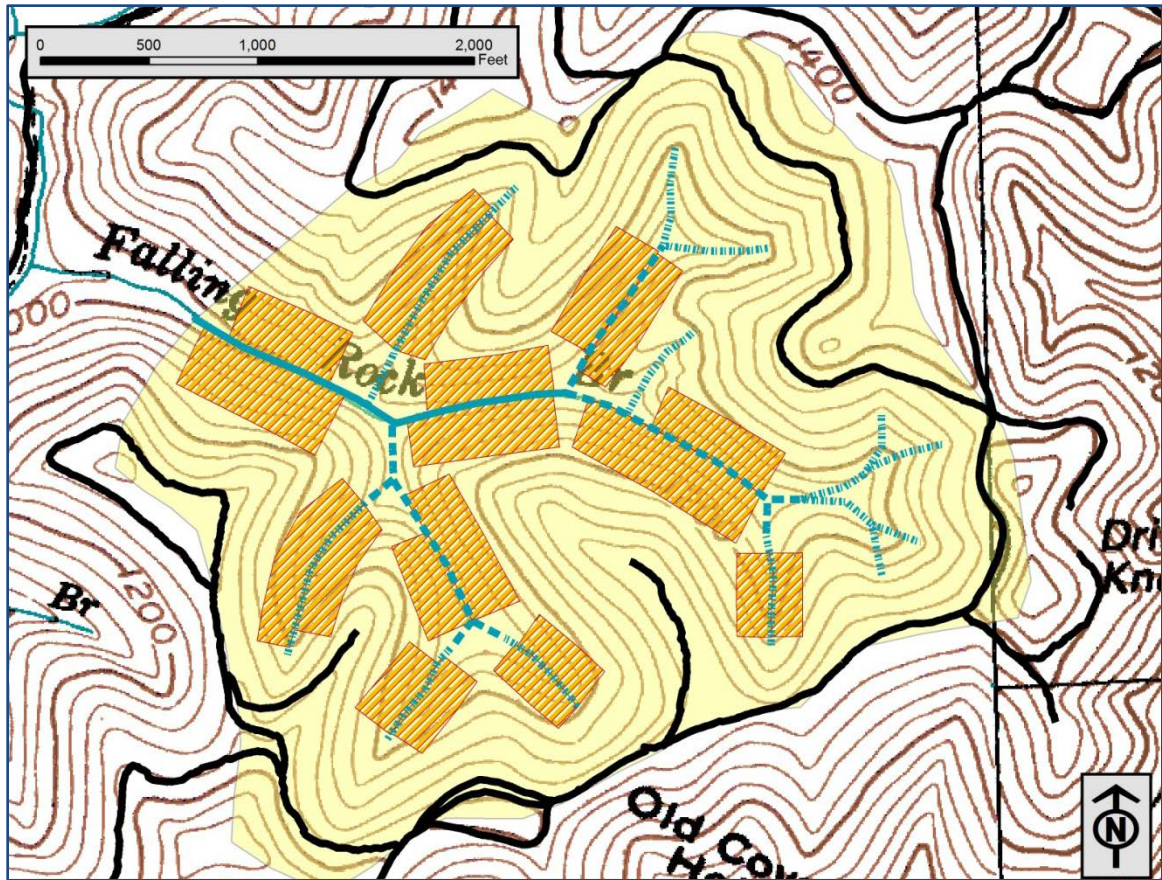


Figure 2.10—Map showing alignment of MultiDAT-captured harvest equipment GPS locations with GeoXM-captured skid trails in the lower section of the 55ft-100% treatment watershed. The skid trail network is represented by black lines, while the GPS locations are represented by green dots. Sediment path study analysis units appearing in this map are represented by hatched orange polygons.



Figure 2.11—Raster map showing relative traffic intensity for all harvest machines on the three study watersheds. Yellow cells are least trafficked, orange is more trafficked, and red is the most trafficked skid trail sections.

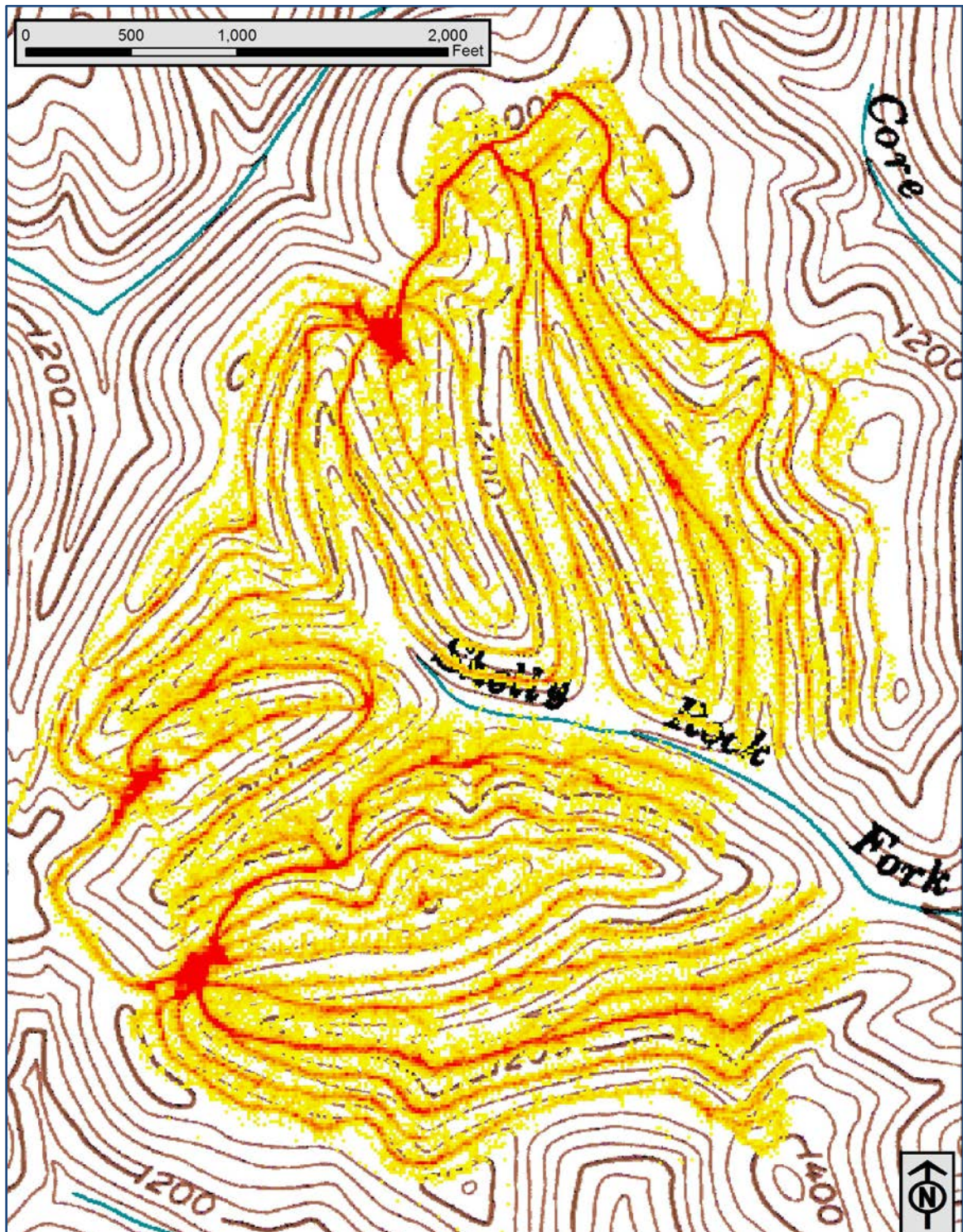


Figure 2.12—Raster map showing relative skidder traffic intensity on the three study watersheds. Yellow cells are least trafficked, orange is more trafficked, and red is the most trafficked skid trail sections.

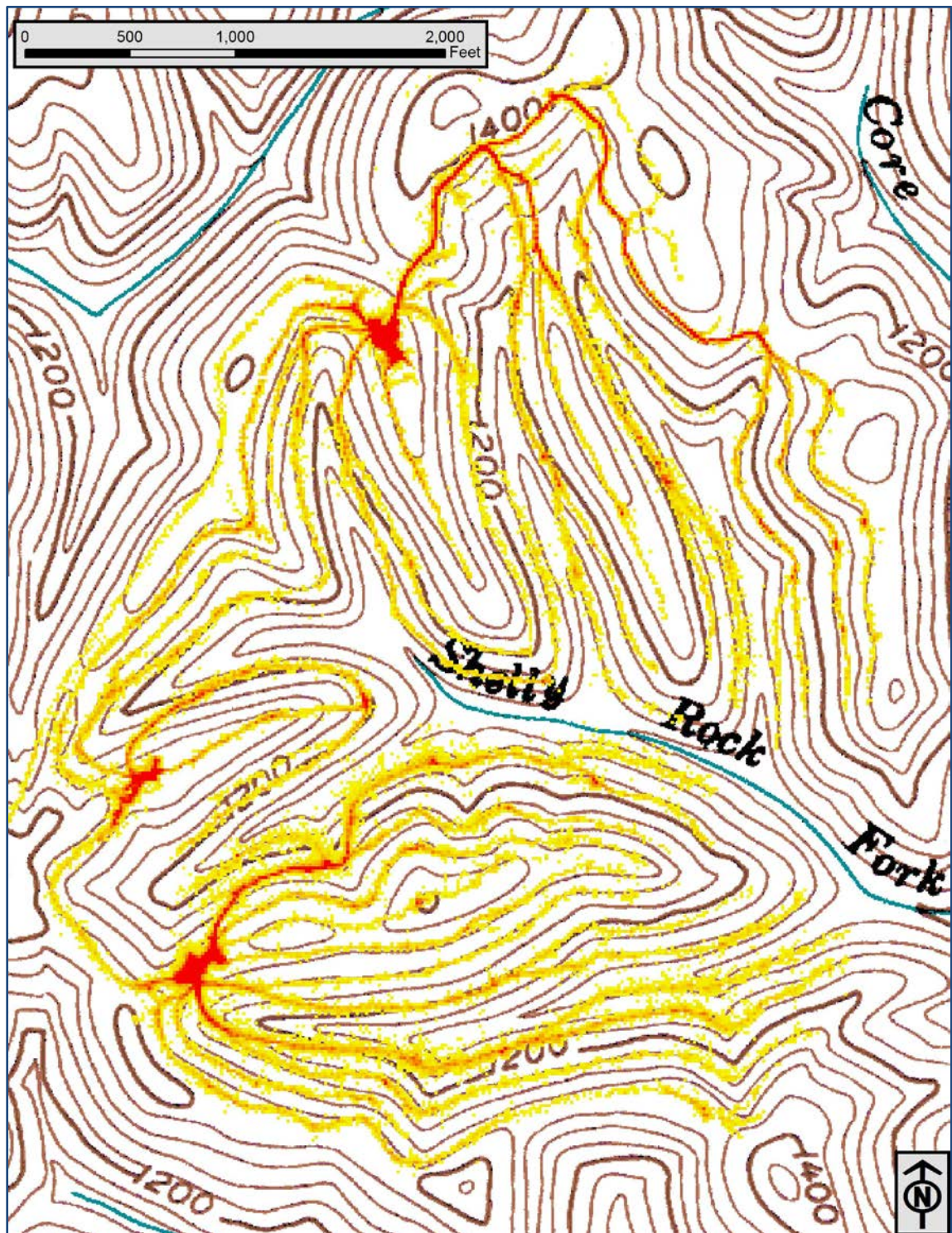


Figure 2.13—Raster map showing relative bulldozer traffic intensity on the three study watersheds. Yellow cells are least trafficked, orange is more trafficked, and red is the most trafficked skid trail sections.

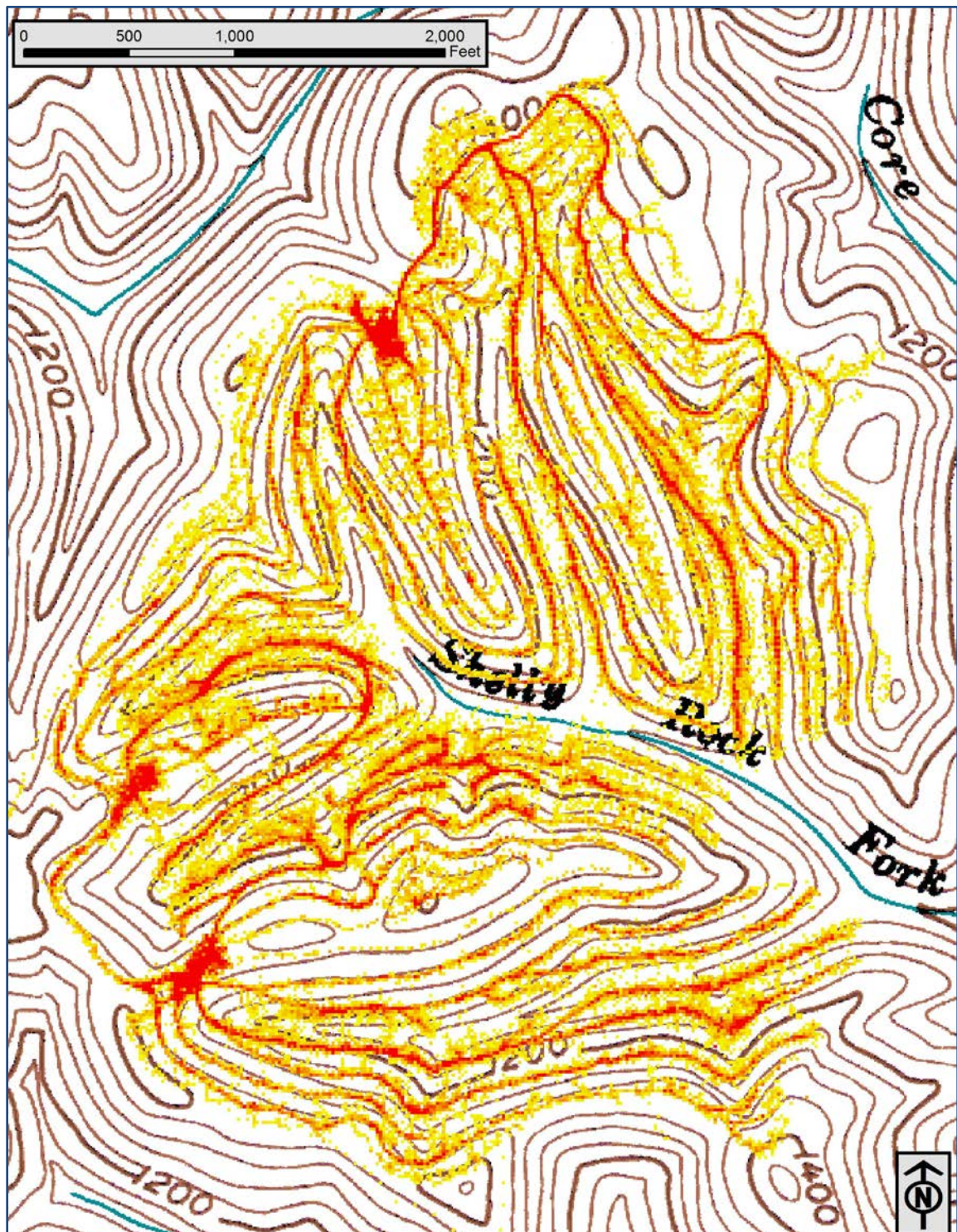


Figure 2.14—Raster map showing relative feller-buncher traffic intensity on the three study watersheds. Yellow cells are least trafficked, orange is more trafficked, and red is the most trafficked skid trail sections. The north-central area of the map shows no feller-buncher traffic due to a hydraulic failure that caused the machine to remain non-operational for several days.

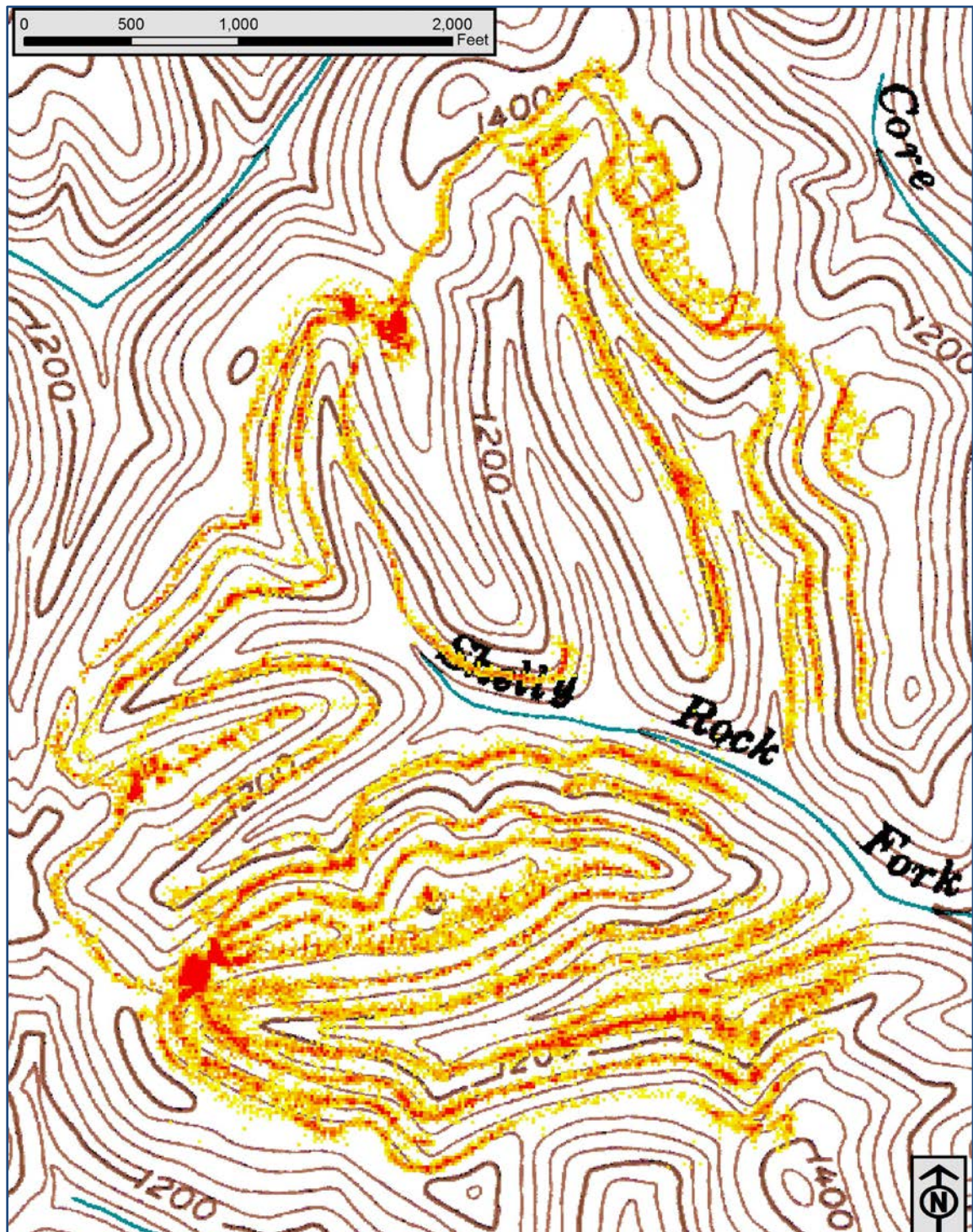


Figure 2.15—Linear regression of machine-caused sediment path distance from source to stream by degree of slope for each path, harvested watersheds only.

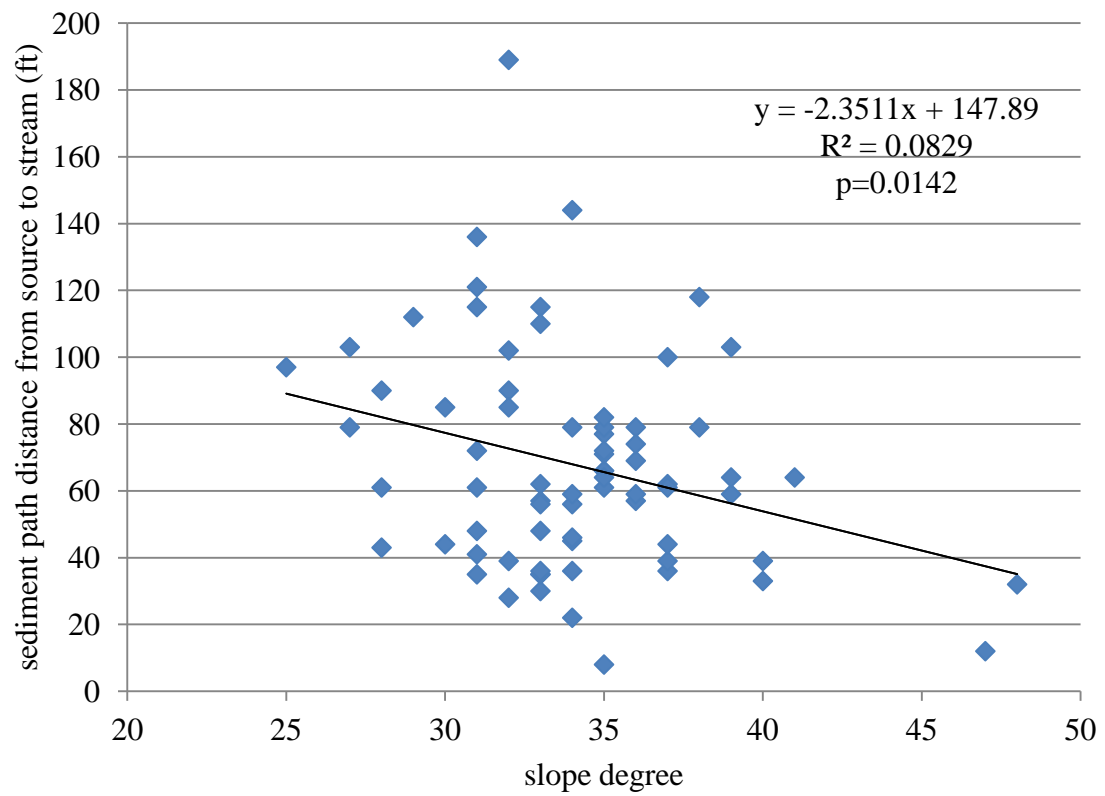


Figure 2.16—Chart showing point of origin of 72 machine-caused sediment paths.

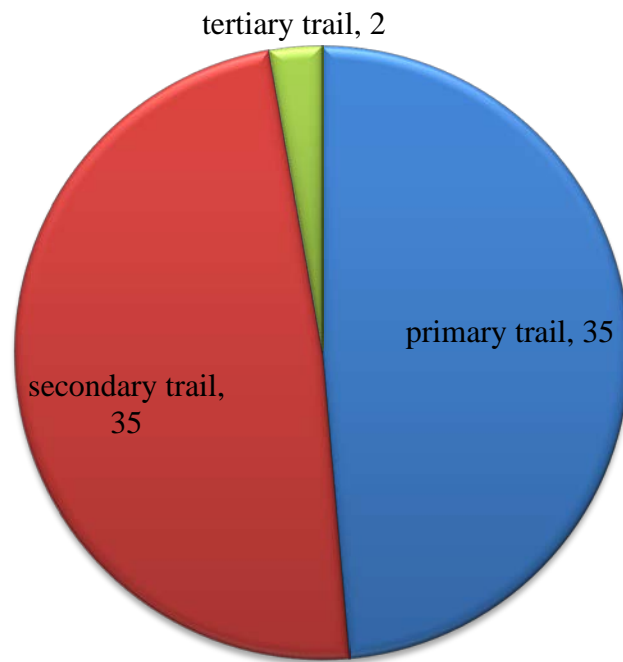


Figure 2.17—Histogram of frequency of machine-caused sediment paths by degree of slope of skid trail section from which the paths originated, harvested watersheds only. Mean slope is 15.3 degrees.

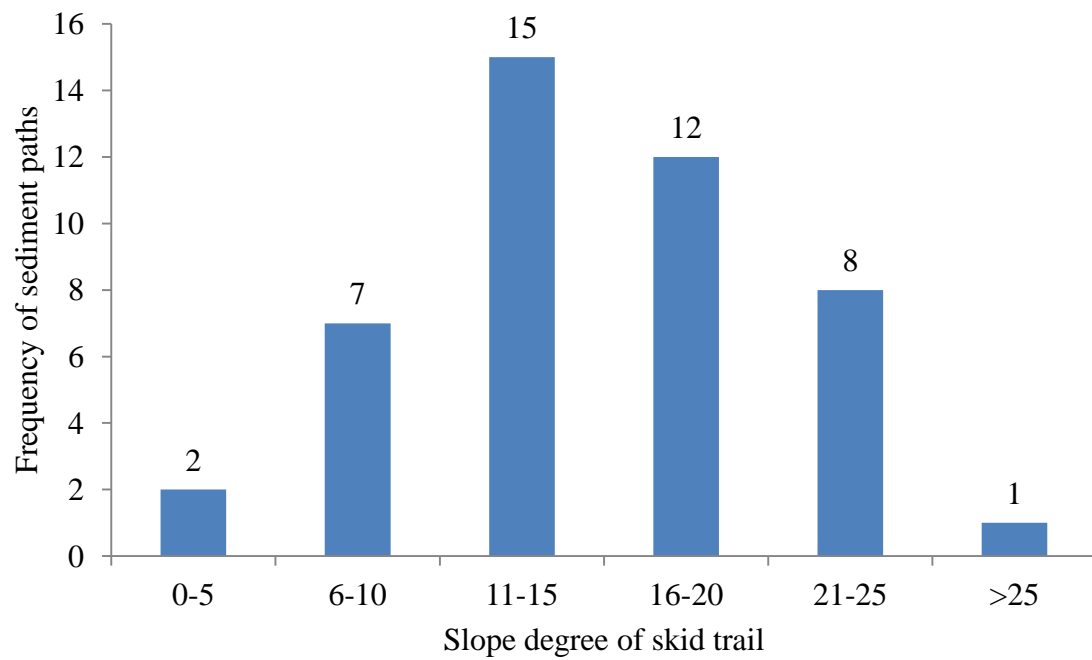


Figure 2.18—Linear regression of undisturbed sediment path distance from source to stream by degree of slope for each path, harvested and control watersheds.

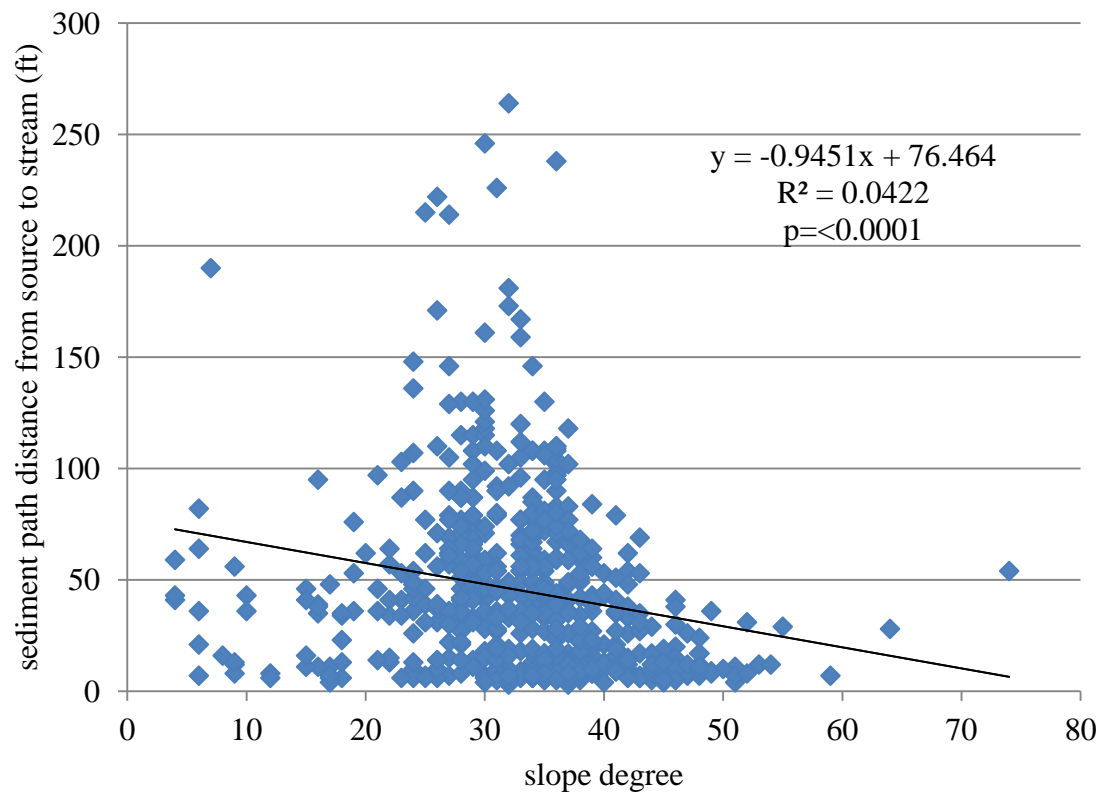


Figure 2.19—Linear regression of combined sediment path distance from source to stream by degree of slope for each path, harvested and control watersheds.

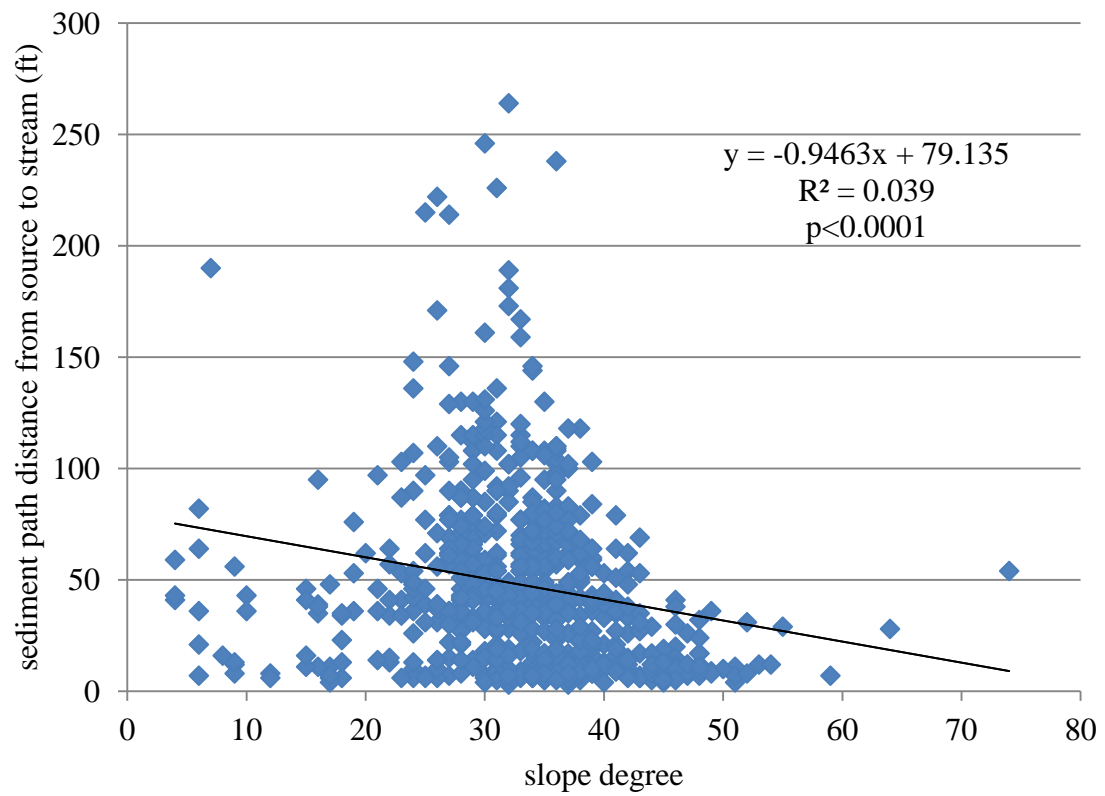


Figure 2.20—Linear regression of number of machine-caused sediment paths per 1,000 ft of stream by number of undisturbed sediment paths per 1,000 ft of stream, harvested watersheds only.

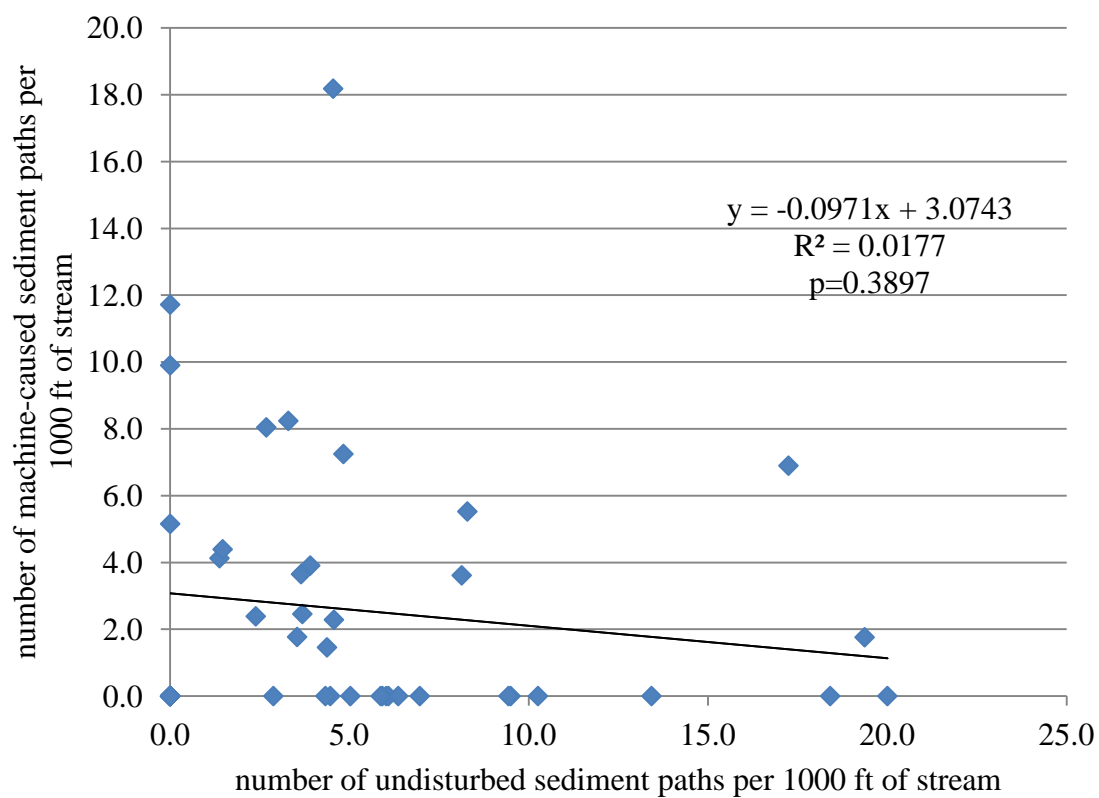
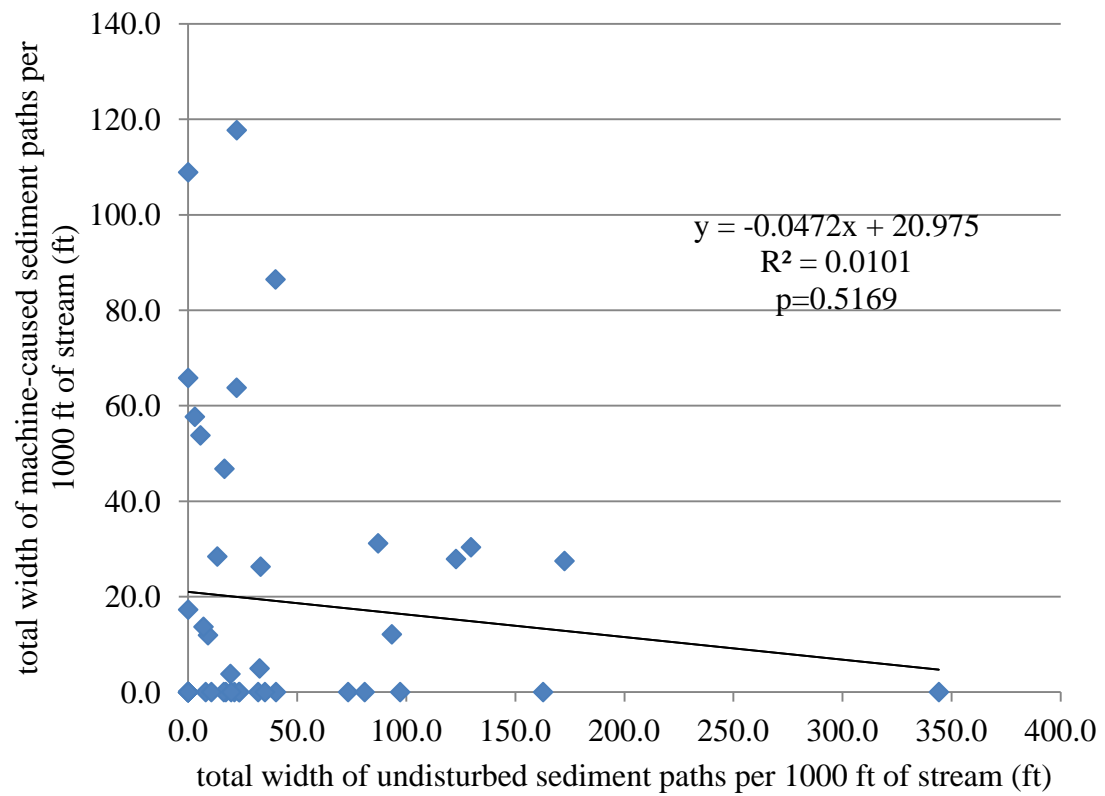


Figure 2.21—Linear regression of total width of machine-caused sediment paths per 1,000 ft of stream by total width of undisturbed sediment paths per 1,000 ft of stream, harvested watersheds only.



CHAPTER III: STREAM CROSSING STUDY

III.1. Introduction

By providing sediment a short pathway by which to enter the streams, stream crossings by the forest road and skid trail network create a high potential for degraded water quality (Lane and Sheridan 2002). In the steeply sloping and highly dissected topography of the Cumberland Plateau in eastern Kentucky, stream crossings are unavoidable in many harvest operations. As noted above, Kentucky's BMP regulations encourage the use of improved or elevated stream crossing techniques, but do not mandate any certain type (Stringer and Perkins 2001). There is a need to quantify the impact of sediment production at stream crossings (Lane and Sheridan 2002), for a wide variety of stream sizes, soil types, terrain, and climate conditions (Taylor, Rummer et al. 1999). Further, cost of these crossing options is a significant factor in choosing which to use in a certain situation, as the cost of improperly siting an improved stream crossing can quickly reduce logging profits. However, there is little published information that quantifies the costs of stream crossing location and construction (Aust, Visser et al. 2003).

A few recent studies have investigated both the potential for stream sedimentation at crossing locations, as well as the different improved crossing techniques that are available to mitigate this sedimentation. In a review of research on the common temporary stream crossing techniques of fords, culverts, and bridges, Taylor et al. (1999) found that fords are generally least expensive, but have greater impacts on water quality; culverts (and the pipe bundle variation) are more expensive to install and maintain than fords but do better at mitigating water quality impacts; and bridges are most expensive,

but have the advantages of not inhibiting the movement of aquatic organisms, and have the lowest water quality impacts. In a study of stream crossing options for the Virginia Polytechnic Institute's Fishburn Forest, Aust et al. (2003) discovered that fords have the potential for significant stream sediment delivery, and conversely that portable skidder bridges were effective in protecting water quality, are low in cost and easy to install, and can be moved after operations are complete. In a study of 101 stream crossings in southeastern Australia, Sheridan and Noske (2007) found that the sediment contribution of gravel surfaced roads was strongly related to truck traffic level, while the sediment contribution of roads with a native soil surface was more dependent on the inherent erodibility of the soil as a surface material. Their study revealed that though there was a high variability in stream sedimentation among crossings, large improvements in water quality can be gained by prioritizing and improving a small number of the worst crossings (Sheridan and Noske 2007). Reeves et al. (2008; 2012) found that using any type of improved stream crossing decreased sediment delivery at the crossings by an average of 97%, and that bridges were significantly better than corrugated metal culverts at reducing sediment inputs. Witt et al. (2013) also found that any type of improved crossing decreases total suspended solids and turbidity compared to unimproved fords, and that bridges are very effective at reducing sediment inputs. Finally, Aust et al. (2011) assert that portable skidder bridges are the improved stream crossing technique that is least disruptive overall to the stream system, while the trail approaches associated with culvert crossings had higher potential erosion than other crossing types.

The objectives of the study were to:

- augment the available research on sediment generation at stream crossings, particularly for site conditions prevalent in the Cumberland Plateau,
- investigate the environmental factors responsible for stream sedimentation at crossing locations, including GPS positional data concerning harvest machine traverses of these crossings, and
- evaluate four different techniques for stream crossing (fords, steel pipes, pipe bundles, and portable bridges) in terms of their ability to prevent stream sedimentation as well as the cost of their use.

III.2. Methods

III.2.i. Study area

The study area for the stream crossing study was the same as that detailed in the overland sediment delivery study (section II.2.i).

III.2.ii. Streamside management zone project and harvest operations

The details of the SMZ project and its harvest operations detailed for the overland sediment delivery study also apply here for the stream crossing study (section II.2.ii).

III.2.iii. Four types of stream crossings

During forest harvest operations, ephemeral stream channels that presented a barrier to log skidding were crossed using one of four techniques: ford, steel pipe used as a culvert

(not a corrugated metal culvert as used in Reeves' study of stream crossing techniques (2008; 2012)), portable skidder bridge, or PVC pipe bundle. Unimproved crossings (fords) were used in the 55ft-50% treatment watershed, while a combination of improved crossing apparatuses (steel pipes, bridges, pipe bundles) were used in the 110ft-100% and 55ft-100% treatment watersheds, as dictated by the overall SMZ study experimental design (table 3.1). As the harvest progressed, potential stream crossing locations were discussed with the logging contractor, with the contractor and the Robinson Forest forester making a decision as to which type of crossing would work best in a particular location, taking note of the feasibility of the type of crossing proposed, as well as attempting to replicate each crossing type. Installation and removal of stream crossings was filmed when possible by UK research personnel, in order to obtain time and cost information for each crossing.

Fords were created by a bulldozer building a skid trail up to both edges of an ephemeral channel, then pushing enough soil into the channel to permit harvest equipment to cross the channel. No brush or other material was introduced into the channel, and no water drainage improvements were made to the channel to allow water to flow under or over the soil placed into the channel. After harvest operations were completed on the section of skid trail encompassing the crossing the fords were retired by a bulldozer removing as much soil as possible from the ephemeral channel, reconstructing the channel to its approximate original contour. Waterbars were then constructed by the bulldozer on both sides of the ford in order to prevent drainage of the nearby skid trail surface from flowing down the stream channel, and a grass seed mix was spread over the exposed soil surface

in and around the channel crossing. Figure 3.1 shows an ephemeral channel ford crossing after retirement.

Steel pipes are commonly used in logging operations in the Cumberland Plateau. Overall, deployment of this improved crossing technique is similar to that of a ford, with the difference being that a steel pipe (usually 8-10" in diameter) is placed in the thalweg of the stream channel, usually by a grapple skidder or bulldozer, before soil is introduced to fill in the channel to create a level trail surface over the channel (figure 3.2). The pipe then allows water to flow through it during storm events. After harvest operations were completed on the section of the skid trail system containing the pipe crossing, the pipe crossings were retired by a bulldozer removing as much soil as possible from the stream channel; the bulldozer removing the pipe by attaching a winch cable and pulling it out, or a skidder using its grapple to lift the pipe out; and then the bulldozer reconstructing the channel to its approximate original contour. Waterbars were then constructed by the bulldozer on both sides of the retired steel pipe crossing in order to prevent drainage of the nearby skid trail surface from flowing down the stream channel, and a grass seed mix was spread over the exposed soil surface in and around the channel crossing. Figure 3.3 shows an ephemeral channel pipe crossing after retirement.

Portable skidder bridges used in the SMZ study were constructed by University of Kentucky forestry personnel out of softwoods harvested on the forest property. Logs were milled into 10 inch by 10 inch square cants, then drilled through to accept threaded rod, secured by nuts on both ends to pull the cants together. A finished bridge panel is

shown in figure 3.4. Three cant panels placed side to side would normally be used for each bridge crossing; however, the use of two layers of bridge panels was due to the use of softwoods to construct the panels (figure 3.5). Bridge panels were put in place by a grapple skidder placing the panels in one at a time, after the skid trail approaches were constructed by bulldozer. Use of the skidder bridge allows the stream channel to stay relatively intact, with minimal introduction of soil. After harvest operations were completed on the skid trail system encompassing the skidder bridge crossings, the bridge crossings were retired by a grapple skidder pulling the panels out one by one. Since the stream channel was relatively undisturbed by installation of the bridge, it was not necessary to have a bulldozer remove soil from the channel. Waterbars were then constructed by the bulldozer on both sides of the retired bridge crossing in order to prevent drainage of the nearby skid trail surface from flowing down the stream channel, and a grass seed mix was spread over the exposed soil surface in and around the channel crossing. Figure 3.6 shows an ephemeral channel bridge crossing after retirement.

The PVC pipe bundle is an improved crossing technique similar in function to a culvert or steel pipe, allowing water to flow through the stream channel crossing area without running through or over loose soil. However, unlike a culvert or pipe, much less soil is necessary to fill the channel to make a level trail surface for traverse by harvest machinery, as the pipe bundle conforms to the channel surface and fills the channel more completely. Pipe bundles were constructed from 4" schedule 40 PVC pipe purchased locally, drilled to accommodate steel cable, with the cable secured in loops with cable clamps, similarly to Mason and Moll (1995) (figure 3.7). Long sections of PVC pipe

were alternated with shorter sections in order to decrease the overall weight of each set, so they could be handled by two people in the field. Several sets of pipe bundles were constructed by University of Kentucky forestry personnel, with lengths of the long pipe sections ranging from 10-20'. For installation of the pipe bundle, the bulldozer constructed the skid trail approaches to the crossing as with installation of a culvert or pipe. Then the logging contractor's crew pulled the pipe bundle into the stream channel by hand, folding the bundle so as to conform to the shape of the channel itself, and leaving a length of steel cable lying downstream for recovery of the bundle after the crossing was retired. After placement in the channel, the bundle was covered with a piece of geotextile to keep soil from getting in between the pipes themselves (figure 3.8), and then was covered with soil by the bulldozer to a depth sufficient to create a level traverse path for harvesting equipment. After harvest operations were completed on the skid trail system encompassing the pipe bundle crossings, the crossings were retired by a bulldozer removing as much soil as possible from the stream channel; the bulldozer removing the pipe bundle by attaching a winch cable to the exposed steel cable loop in the channel and pulling it out, or a skidder using its grapple to grab and lift the pipe bundle out; and then the bulldozer reconstructing the channel to its approximate original contour. Waterbars were then constructed by the bulldozer on both sides of the retired pipe bundle crossing in order to prevent drainage of the nearby skid trail surface from flowing down the stream channel, and a grass seed mix was spread over the exposed soil surface in and around the channel crossing. Figure 3.9 shows an ephemeral channel pipe bundle crossing after retirement.

III.2.iv. Water sampling procedures

Immediately after installation of each stream channel crossing by the harvest contractor, University of Kentucky research personnel placed an ISCO portable water sampler (Teledyne ISCO, Lincoln, Nebraska) in the stream channel below each crossing. ISCO locations were recorded using a Trimble GeoXM handheld GPS unit (Trimble Navigation Limited, Sunnyvale, CA). During storm events that resulted in flow in the ephemeral channels, a liquid level actuator placed directly in the streambed activated water sampling (Witt, Barton et al. 2013). For the 24 hour period beginning with initiation of channel flow, a 200 ml water sample was taken every 30 minutes, for a composite sample of 9.4 L (Witt, Barton et al. 2013). A 1.5 L subsample was used for analysis of two water quality parameters, total suspended solids (TSS) and turbidity (Witt, Barton et al. 2013).

Determination of TSS level was made according to American Public Health Association guidelines, using a 0.45 μm filter (Witt, Barton et al. 2013). A Hanna portable meter (model HI 93703, Hanna Instruments, Woonsocket, Rhode Island) was used to determine turbidity, measured in formazin turbidity units (Witt, Barton et al. 2013). All rain events resulting in TSS and turbidity readings, from the date of stream crossing installation through December 2010, were log transformed and averaged to obtain the response variable used in analysis (Witt, Barton et al. 2013). However, due to a very dry period during harvest operations, no rain events were recorded for any of the stream crossings during installation, use, or retirement. Therefore, all water quality measurements taken from the stream crossing locations are from the post-retirement period.

III.2.v. GPS tracking and GIS analysis

Experimental units subjected to statistical analysis for this study were created as polygon shapefiles in ArcMap. Polygons were drawn to encompass a particular area where an ephemeral stream channel was crossed during harvest operations. Each of these experimental units is a sub-watershed, encompassing the land area drained by the stream channel, from the ridgeline to the point downstream where the ISCO portable water sampler was located. Experimental units in the harvest watersheds include the skid road and trail sections built and used during harvest operations, while those in the control watersheds include the sections of existing forest road system. As an example, figure 3.10 shows analysis units for the 55ft-100% treatment, while figure 3.11 is a closeup of a unit in the 55ft-100% treatment, showing where the skid trail system crossed an ephemeral channel.

An attribute table for the harvested and control experimental units was created in ArcMap, in order to characterize each experimental unit as to several variables that may have an influence on TSS values taken below the crossing. For each harvested experimental unit, treatment-prescribed buffer width and canopy retention percent were entered, as well as treatment designation number 1, 2, or 3. A value for crossing type was entered: 1 for unimproved ford, 2 for steel pipe, 3 for PVC pipe bundle, and 4 for portable skidder bridge. Experimental unit acreage was calculated using the calculate geometry tool in ArcMap. Average and maximum slope degree values for each unit were derived from 10 meter digital elevation model (DEM) data. Average aspect for each unit, derived from the 10 meter DEM, was transformed to a moisture index from 0 to 2, with 0

representing the driest slopes (southwest exposure) and 2 representing the wettest slopes (northeast exposure), with a value of 1 representing a slope facing either northwest or southeast and hence an intermediate moisture index (Beers, Dress et al. 1966). A post-harvest residual basal area value for each experimental unit was determined by field measurement using a 10 factor prism at regularly spaced upland and streamside locations within each unit. An average upland basal area and an average streamside basal area were calculated, then those two values were averaged to get the average post-harvest residual basal area for that experimental unit. The average slope degree value of the stream channel at the crossing in the harvest units was determined with a clinometer, as well as the slope of the skid trail as it approached the crossing from both sides of the stream channel. In the unharvested controls, the average stream channel slope was determined from 10 meter DEM data, by averaging all slope points within 20 ft of the shapefile line representing the ephemeral channel. The maximum skid trail approach slope was also entered into the attribute table. The distance from the edge of the stream channel at the crossing to the nearest water control structure or reverse in skid trail grade was measured in feet, for both skid trail approaches to each crossing. The maximum distance from crossing to water control was also entered into the attribute table.

The total number of GPS positions present within the experimental unit border was calculated and entered into the attribute table as a total traffic intensity value for that unit, then an index value of machine traffic intensity was calculated by dividing this total traffic intensity value by the area of the unit in acres. The total machine traffic intensity value was broken up into traffic intensities associated with skidder, dozer, and feller-

buncher traffic within each unit and entered into the attribute table; index values for each machine type were calculated as in the sediment path study, dividing the total number of GPS positions within an experimental unit associated with each type of machine by the acreage of the unit. Skid trail distances were measured within each unit using the measure tool in ArcMap, and calculated as feet of primary skid trail, secondary skid trail, tertiary skid trail, and total feet of skid trail (see table 2.3 of the sediment path study above for skid trail type descriptions). A skid trail density index value was calculated by multiplying the total feet of skid trail within each unit by 16 (an average skid trail width throughout the harvest units), then dividing the total square feet of skid trail within the analysis unit by the area of the unit in acres, yielding a value of square feet of skid trail per acre.

For each stream crossing point, number of machine traverses during harvest activity was determined from MultiDAT data exported as line shapefiles into ArcMap. Each transit across the stream was counted as one traverse, by zooming in on the stream crossing in ArcMap and counting the number of line segments derived from the GPS data that crossed the stream. Care was taken to eliminate false crossings resulting from the bouncing around of the GPS point fix. The total number of machine traverses was entered into the attribute table for each stream crossing, as well as a value for number of skidder traverses, number of dozer traverses, and number of feller-buncher traverses.

The morphology of each stream crossing was documented after crossing retirement to determine an approximate volume of backfilled soil that was introduced into the channel

in order to build up the trail surface sufficiently for harvest machine traffic. Width of the skid trail on each side of the crossing was measured, along with the width of the crossing itself on the upstream and downstream side, and the depth of the thalweg at both upstream and downstream sides. Trail widths, crossing widths, and thalweg depths were each averaged, and an approximate fill volume was calculated for the resulting triangular prism, with this fill volume entered into the shapefile attribute table. The approximate volume of the steel pipe or pipe bundle introduced into the stream channel was subtracted from the fill volume. An approximate surface area of the retired crossing subject to erosion was calculated by drawing a three dimensional figure of the triangular prism representing each filled stream crossing in version 8 of Google SketchUp (Google, Mountain View, CA), and using the program to determine the surface area of the two quadrilaterals on the bottom of the prism, representing the two sections of reclaimed stream channel, and adding these two values. As an example, figure 3.12 shows the triangular prism created in SketchUp for a stream crossing in the 55ft-50% treatment watershed.

Experimental units encompassing ephemeral stream sections that were crossed more than once presented a special problem for analysis. It was not possible to merely treat the multiple stream crossings as distinct and calculate all variables for each independently, as some of the factors relating to sediment production at the stream crossings are additive. For example, the number of machine traverses at a crossing that occurs upstream from another one would theoretically affect sediment levels at the lower crossing. In these cases, the variables that would be additive were summed in the case of the lower

crossing. These included number of machine traverses, fill volume, and erosional surface area. Also, the values for maximum slope of trail sections approaching the crossing and maximum distance to water control structure are the maxima for both of the crossings.

III.2.vi. Time study of stream crossing options

In order to determine the relative cost of each of the four types of stream crossings, it was necessary to quantify the amount of time each type of crossing takes to install, remove, and retire. With this time data, along with the materials and labor cost for each of the different crossing structures, the relative cost of each crossing type can be obtained. To this end, stream crossing installations, removals, and retirements were filmed with a handheld video camera. These films were then analyzed to obtain installation time, removal time, and retirement time for each type of crossing.

III.2.vii. Data analysis

Maps of experimental units in each watershed are shown in figures 3.13 through 3.17. Figure 3.18 shows two steel pipe crossings studied in the 110ft-100% treatment watershed Wet Fork, which were added to the analysis for the first part of this stream crossing study, though these crossings were not included in experimental units where environmental and harvesting factors were analyzed, due to the lack of reliable GPS data for the Wet Fork watershed.

All statistical analysis was performed using JMP version 9 (SAS Institute Inc., Cary, NC). Linear models and linear regressions were used in order to determine significant

factors in increases in turbidity levels, and were created by the standard least squares procedure, with pairwise multivariate analyses run to eliminate highly correlated variables. As the study area was quite large with a high degree of micro- and macrotopographic diversity, significance was set at the $\alpha=0.10$ level, in order to capture indications of significance that would be missed at the $\alpha=0.05$ level. In some instances, significance levels above $\alpha=0.10$ are discussed when they are slightly above that level, and when trends in nearly significant variables are notable.

TSS and turbidity measurements were log transformed to correct the positive skew in the datasets, resulting in normal distribution of the transformed data (Witt, Barton et al. 2013). Also, as a strong linear relationship was observed between TSS and turbidity measurements ($p<0.001$, $R^2=0.71$) (Witt, Barton et al. 2013), a mean log transformed turbidity value was used as the response variable in linear model analysis, rather than running separate models for TSS and turbidity.

III.3. Results and discussion

III.3.i. Performance of MultiDAT GPS dataloggers during harvest operations

For a summary of the performance of the MultiDAT GPS dataloggers during harvest operations, see the results of the sediment path study (section II.3.i).

Figure 3.19 shows an example of the line shapefile output from the GPS data, which enabled determination of the number of harvest machine traverses over each stream crossing. As the figure indicates, each individual track must be evaluated to determine the

number of traverses, as the resolution of the GPS data was not fine enough to track the machines precisely over the stream crossing. However, by discarding obviously erroneous GPS data and evaluating each track, the number of traverses can be accurately obtained. This shows that the MultiDAT dataloggers are capable of tracking the number of machine traverses over a certain point such as a stream crossing location, enabling analysis of the impact of machine traffic at that point. Table 3.1 details the stream crossings that were studied, the type of crossing at each location, the number of traverses by harvest machine type over that crossing, and the average log-transformed turbidity value obtained by water quality monitoring.

III.3.ii. Summary of effects of improved crossings and treatments on differences in total suspended solids (TSS) and turbidity from Witt et al. (2013)

The effect of the three improved stream crossing options and the three SMZ treatments on differences in TSS and turbidity measured at these crossings is reported in Witt et al. (2013), and is summarized here.

Though the treatment design makes it difficult to distinguish between the effects of the use of improved stream crossings, the establishment of an SMZ around ephemeral stream channels, and the retention of channel bank trees (see table 2.1 of the sediment path study for the treatment design structure), significant differences were observed between the 55ft-50% treatment stream crossings (where no SMZ was present around ephemeral stream channels, no channel bank trees were retained, and unimproved fords were used to cross stream channels) and the 110ft-100% and 55ft-100% treatments stream crossings,

which did include additional protections for ephemeral stream channels. TSS was over 4 times greater in the 55ft-50% treatment stream crossings than in the 110ft-100% treatment crossings, and nearly 6 times greater than in the 55ft-100% treatment crossings. Turbidity was 2.5 times greater for the 55ft-50% treatment crossings than the 110ft-100% treatment crossings, and more than 4 times higher than in the 55ft-100% treatment crossings. This indicates that additional protections around ephemeral stream channels such as improved stream crossings, the retention of channel bank trees, and an SMZ wherein no harvest machine traffic was allowed contribute to a reduction in stream sedimentation rates during forest harvest activity near these ephemeral stream channels.

Differences observed among the TSS and turbidity levels from the various types of stream crossings are highly significant. Bridges reduced TSS levels by 88% compared to unimproved ford crossings, while steel pipes reduced TSS by 85%, and pipe bundles reduced TSS by 77%. Similarly, turbidity levels decreased with the use of improved crossings compared to the unimproved ford crossings, bridges (83%), steel pipes (77%), and pipe bundles (68%). However, there were no significant differences among the three improved crossing types. Turbidity increased between the unharvested controls and the bridge, steel pipe, and pipe bundle crossings; however, TSS was only higher than unharvested controls when using pipe bundles, while bridges and steel pipes showed TSS levels similar to unharvested channels. These results show that any type of improved stream crossing reduces stream sedimentation rates compared to unimproved ford crossings, though differences in the three improved crossing types were not remarkable.

While Witt et al. (2013) reported results for treatment and stream crossing type effects on stream TSS and turbidity levels, the present study reports the effects that various environmental and harvest operations factors had in leading to the above reported turbidity levels attributed to the different types of stream crossings. As mentioned in the methods section for this study, turbidity is used as a measure of stream sedimentation here, as TSS and turbidity showed a strong linear relationship (Witt, Barton et al. 2013), and running separate models for each would be redundant.

III.3.iii. Environmental and operational factors correlated with turbidity levels in controls

Linear regression and modeling was undertaken for the control analysis units and harvest treatment analysis units separately, as the suite of variables under consideration differs markedly for the control and the treatment stream crossings. Prior to linear modeling, pairwise multivariate analyses were run to identify and eliminate those independent variables that were highly correlated so as not to negatively impact model performance. Results of this analysis for the control analysis units indicated correlations among several variables (table 3.2). Degree of ephemeral channel slope at the stream crossing location was correlated with moisture index of the analysis unit (0.8518) and with basal area retained in the analysis unit (0.926). Mean slope of the analysis unit was correlated with maximum slope of the analysis unit (0.9333) and with moisture index (0.953), while maximum slope of the analysis unit was also correlated with moisture index (0.8046). Trail density was correlated with channel slope (0.7815) and with moisture index (0.8205).

Given these correlations and the small sample size for the control analysis units ($n=4$), the independent variables of interest were regressed individually with turbidity for the control analysis units. These included: degree of channel slope at the water sampling location, maximum analysis unit slope, moisture index of the analysis unit, average basal area of the analysis unit, and trail density within the analysis unit. Trails within the control analysis units were lightly used sections of forest road and had little in common with the bladed and heavily used trail system of the treatment analysis units; however, their presence and possible influence on sediment delivery into the ephemeral stream channels could not be fully ignored, so they were included in the analysis.

Table 3.3 summarizes significant independent variables in the regression analysis performed for the control analysis units. Regression of moisture index of the analysis unit with mean turbidity level did show a significant relationship ($p=0.0841$), with the correlation in the positive direction. This indicates that for the control analysis units that are wetter (i.e. with more northeasterly aspects), the greater amount of soil moisture leads to a greater potential for sediment delivery to the stream network near the water sampling location. Trail density also showed a significant positive relationship with mean turbidity level ($p=0.0232$), indicating that a greater density of trails near a stream crossing location in the control analysis units leads to greater sediment delivery to the stream network at this location. Linear regression showed no significant relationship in the control analysis units with degree of channel slope, maximum analysis unit slope, or average basal area of the analysis unit.

III.3.iv. Environmental and operational factors correlated with turbidity levels in treatments

Running pairwise multivariate analyses on the set of independent variables under consideration for the treatment analysis units resulted in fewer correlations (table 3.2). Maximum analysis unit slope was correlated with average analysis unit slope (0.8382); average analysis unit slope was eliminated from modeling as it was also correlated with moisture index (0.7521). The measure of surface area subject to erosion after retirement of the stream crossing was eliminated as it was correlated with approximate fill volume of the stream crossing (0.9354), as well as with the maximum slope of the skid trail approaches to the stream crossing (0.7558). Traffic area indices for the treatment analysis units, both combined and for individual harvest machine types, were eliminated from modeling as the more interesting variable for the stream crossings was number of machine traverses over the stream crossing.

For the treatments, linear models created included:

1. environmental variables for all crossing types (degree of channel slope at the stream crossing, maximum analysis unit slope, and moisture index of the analysis unit)
2. harvest operations variables for all crossing types (average residual basal area of the analysis unit, and trail density of the analysis unit)
3. stream crossing morphology variables for all crossing types (maximum slope of skid trails approaching the stream crossing, maximum number of feet to a water control structure from the stream crossing location, and approximate volume of

soil necessary to fill the stream crossing for harvest machine travel over the crossing location).

Along with these three models, linear models and regressions were run for each type of stream crossing individually (unimproved fords, steel pipes, PVC pipe bundles, and portable skidder bridges), as a combined group including all 4 crossing types, and as a group including the 3 crossing types other than bridges, to investigate the effect of harvest machine traverses of the stream crossing. These models and regressions used log-transformed mean turbidity as the response variable, and the number of machine traverses for the independent variable (total machine traverses, skidder traverses, bulldozer traverses, and feller-buncher traverses).

Table 3.4 summarizes significant or nearly significant independent variables in the environmental, harvest operations, and stream crossing morphology linear models. In the environmental model, stream channel slope at the stream crossing was significantly positively related to turbidity ($p=0.0665$). This indicates that as the stream channel slope increases, the velocity of water in the channel also increases, which leads to an increase in turbidity. Neither the maximum slope of the analysis unit containing the crossing, nor the moisture index value of the analysis unit were significant in this model.

In the harvest operations model, no factors were significantly related to turbidity.

However, the average residual basal area of the analysis unit was nearly significantly negatively related to turbidity ($p=0.1168$). Though not significant, this may mean that the more basal area left in the area near a stream crossing, the less disturbance produced near

the crossing, leading to a lower stream turbidity level below the crossing. Trail density in the analysis unit containing the stream crossing was not significantly related to turbidity.

In the stream crossing morphology model, no factors were significantly related to turbidity, though the maximum slope of the trail approaching the crossing was nearly positively so ($p=0.1169$). Though not significant, this may indicate that a trail system with greater slopes approaching the stream crossing location will lead to increased stream turbidity. The approximate volume of fill needed to bring the level of the stream crossing up to the level of the skid trails leading to it was not significant in the model, nor was the maximum distance to a water control structure from the crossing location. The latter is not surprising, as waterbars were placed relatively near the crossing locations during retirement of those sections of the skid trail system.

When looking at each type of stream crossing separately, linear regression of harvest machine traverses of the stream crossings with turbidity showed no significance as to number of traverses, nor to the number of traverses of the different machine types. If anything, a general trend toward decreased turbidity with increased number of traverses might be noted. This was never anywhere approaching significance so it is not advisable to draw strong conclusions from this trend. However, in light of the results from the sediment path study that indicated the possibility that some types of traffic (especially skidder traffic) led to increased soil compaction and therefore decreased overland sediment delivery from the skid trail network, it is tempting to think the same forces may be at work at the stream crossings.

Regression and modeling of harvest machine traverses when combining all 4 stream crossing types as one group also showed no significance as to number of traverses with all machine types combined, to number of traverses with each type of machine in the same model, nor to number of traverses of each machine type looked at individually. However, there was one interesting set of results when looking at the three stream crossing types other than bridges. The reasoning behind this modeling effort was that as bridges are placed across the stream channel without major modification of the channel itself, and no fill is added to the channel to level the crossing as is the case with the other crossing types, it might be possible to see significant factors in turbidity response when taking bridges out of the model. This raises the sample size of crossings from $n=3$ to $n=9$ (3 each of fords, steel pipes, and pipe bundles). Modeling for turbidity with the 3 non-bridge crossings grouped together, using number of machine traverses for all machine types combined, showed no significance, nor was any shown when regressing the individual machine type traverses against turbidity.

However, the model with number of traverses of the individual machine types as independent variables in the same model showed an interesting result (table 3.5). In this model, number of skidder traverses over the three non-bridge crossing types was significant ($p=0.0515$), and was negatively correlated with turbidity. Feller-buncher traverses were not significant, but was near, and was positively correlated with turbidity ($p=0.1297$). Bulldozer traverses were not significantly related to turbidity. This model is interesting mainly for the fact that the results mirror what was found in the sediment path study, that skidder traffic was negatively related to sediment production, while feller-

buncher traffic churns up the soil near the stream crossings as it moves, leading to increased sediment delivery. What remains to be explained here is why bulldozer traffic, using tracks for movement as the feller-buncher did in this study, is not related to turbidity as well. One difference in bulldozer and feller-buncher movement observed during this study is that while the bulldozers were frequently dragging logs with a winch cable, the feller-buncher never was. Especially in the steep terrain common in the Cumberland Plateau, bulldozers are used for nearly every logging task, which means that when a skidder is not nearby, they are often seen dragging logs to staging areas for the skidder to pick up on its return. Feller-bunchers never drag logs in this fashion, but always merely stack the logs in skidder-accessible locations as they are cut. Dragging the logs across stream crossings has an effect that was not measured in this study and would be difficult to quantify, but was observed many times. As the logs are dragged behind the skidders and bulldozers, they tend to smooth the trail surface around bends when they are at an angle to the direction of travel of the machine. This smoothing action may help to compact the trail surface, leaving less soil open to dislodging and erosion into the stream at the crossings. Also, the dragged logs can create depressions in the trail surface when they are in line with the direction of travel of the machine, and these linear depressions running down the center of the trail could funnel the flow of water down the trail directly to a water control structure, where it is dispersed onto the forest floor before reaching the crossing itself. Feller-buncher traffic would not have either the smoothing or channeling action of a bulldozer or skidder dragging logs.

This theory, however, is only speculative, and care should be taken in drawing too strong a conclusion from the lack of significance of the bulldozer traffic's relationship to turbidity. It must be remembered as well that all turbidity data was obtained after retirement of the crossing locations, and that the action of the bulldozers while retiring the crossings and the nearby skid trail sections would likely obliterate any smoothing and channeling left behind by dragging logs near the crossings. It is also possible that the traffic of the bulldozers during trail and crossing retirement muddled the picture of bulldozer traffic's relationship to turbidity, as the bulldozers were not dragging logs during retirement, and then their traffic would be very similar to the feller-buncher's.

Finally, it should be noted that any separation of the total harvest machine traffic into the different types of machine, and then drawing conclusions from the individual machine types' traffic levels, is speculative as well. This study was not done in a manner that allows distinct separation of the different types of machine traffic (i.e. we were not able to run only the skidders over stream crossings, excluding the bulldozers and feller-bunchers, and take turbidity readings that would only be associated with skidder traffic). The GPS data gives us information on the amount of each type of machine traffic over the different crossings, but it is not possible to strongly tie each individual type of machine traffic over the crossings to a certain fraction of the total turbidity level sampled at each crossing.

III.3.iv. Time study of installation, removal, and retirement of improved stream crossings

During harvest operations, the installation, removal, and retirement of the four stream crossing options were filmed if possible, and the films were later analyzed to determine elapsed time during these elements of stream crossing use. While the film record is not complete, enough time record data exists to approximately quantify the average amount of time needed for installation, removal, and retirement of the four stream crossing types used in the study (table 3.6).

The installation of one unimproved ford stream crossing was filmed in the 55ft-50% treatment watershed, while the retirement of two fords were filmed in that watershed. Installation of the filmed ford crossing took 00:31:50, while retirement of the two filmed fords took 00:34:08 and 00:38:47. As the three fords were similar in size and morphology, an installation time of 00:31:50 can be used as the approximate average time to install an unimproved ford crossing in an ephemeral channel in the steep terrain of the harvest area. Averaging the two ford retirement times gives an approximate unimproved ford retirement time of 00:36:28. Approximate average total time necessary for ford crossing use then is 01:08:18.

The installation of one steel pipe was filmed in the 110ft-100% treatment watershed Shelly Rock West. This steel pipe installation was completed in 00:11:05. The removal of a steel pipe was filmed in the 110ft-100% treatment watershed Wet Fork; though this watershed was not involved in the present study's results, the steel pipe removal and

retirement filmed there can be used to approximate the time necessary to remove and retire a steel pipe stream crossing. This removal and retirement was accomplished in 00:05:14. Two more steel pipe removals and retirements were filmed in the 110ft-100% treatment watershed Shelly Rock West. These steel pipe stream crossings were not immediately retired after removal of the steel pipe, and film does not exist of their retirement. However, given their quick removal and the amount of time necessary to retire similar steel pipe crossings, it can be estimated that removal and retirement of these 2 steel pipe stream crossings took around 00:05:00 each, very close to the 00:05:14 removal and retirement time of the Wet Fork steel pipe stream crossing. Therefore, for steel pipe stream crossing installation, an approximate average time of 00:11:05 can be used, while for steel pipe stream crossing removal and retirement, an approximate time of 00:05:14 can be used, for a total average approximate time of 00:16:19.

Three complete pipe bundle stream crossing installations, removals, and retirements were filmed, 2 in the 55ft-100% treatment watershed Shelly Rock South, and 1 in the 110ft-100% treatment watershed Shelly Rock West. Two of these were quite similar, with installation times of 00:20:00 and 00:22:24, and removal and retirement times of 00:51:17 and 00:57:51. The third pipe bundle was wildly more difficult to install, remove, and retire, due to the morphology of the ephemeral stream channel it was placed in. While the first two pipe bundle crossings mentioned had approximate fill volumes necessary to level the skid trail over the crossing of 409 and 744 cubic ft, the third pipe bundle crossing needed approximately 5752 cubic ft of fill to level the skid trail over the stream crossing. This was due to the width and depth of the ephemeral channel where the

pipe bundle stream crossing was installed, and caused the installation, removal, and retirement times to be vastly out of line with the other two pipe bundle crossings. Installation of this difficult pipe bundle crossings took approximately 04:30:00, while its removal and retirement took 02:08:10. For this reason, this third pipe bundle stream crossing will not be included in figuring an average installation, removal, and retirement time for the pipe bundles, and illustrates the necessity of wisely choosing where to install a crossing over an ephemeral stream channel. Ignoring the difficult pipe bundle crossing, an average installation time of 00:21:12 can be used for pipe bundle stream crossings, while an average removal and retirement time of 00:54:34 can be used, for a total average approximate time of 01:15:46.

Three portable skidder bridge stream crossing installations were filmed, two in the 55ft-100% treatment watershed Shelly Rock South, and one in the 110ft-100% treatment watershed Shelly Rock West. Installation times for these three bridge crossings were 00:09:06, 00:12:40, and 00:15:05, for an average installation time of 00:12:17. Removal and retirement of two of these bridges was filmed, taking 00:12:18 and 00:09:47, for an average removal and retirement time of 00:11:03. Average approximate total time for portable skidder bridge stream crossing use is 00:23:20.

Though these times are based on a limited sample size, they were observed during normal harvesting operations of two different logging crews using a similar suite of equipment, and can be taken as relatively normal for the installation, removal, and retirement of the four types of stream crossings used in this study. Looking at the total time investment for

these crossing types, these factors stand out: the time investment for steel pipe and bridges crossings is roughly similar, the time investment for ford and pipe bundle crossings is also roughly similar, but steel pipes and bridges took roughly only a quarter of the time invested for fords and pipe bundles.

III.4. Summary of stream crossing study

This study shows that paying attention to forest operations in small headwater stream systems, especially in and around ephemeral channels and the locations where the skid trail system crosses these ephemeral channels, can lead to significant reductions in stream system sediment levels. As Sheridan and Noske pointed out (2007), the high variability among crossings means that large improvements in sediment reduction can be obtained by careful attention to a small number of the worst crossings. The use of improved stream crossings, the establishment of an SMZ wherein harvest equipment use is limited, and the retention of channel bank trees leads to reductions in TSS and turbidity levels, though the design of this study makes it difficult to separate the relative contributions of each of these factors (Witt, Barton et al. 2013). The results reported here do show that the use of any type of improved crossing (steel pipe, pipe bundle, bridge) has a pronounced effect on reduction of sediment levels (Witt, Barton et al. 2013), which is consistent with results obtained by Reeves et al. (2008; 2012). Though this study found no remarkable differences in the sediment reductions obtained by the different improved crossing types (Witt, Barton et al. 2013), Reeves et al. (2008; 2012) did find that bridges were significantly lower than steel pipes in sediment production.

The finding of this study that moisture index (a function of aspect) and trail density in the unharvested control units were significantly positively related to turbidity suggests that careful attention to trail system construction and stream crossing citing, especially on wetter aspects, can help in reducing stream sedimentation levels. Also, as degree of stream channel slope at a stream crossing was significantly positively related and maximum degree of trail slope leading to a stream crossing was nearly significantly positively related to turbidity in the harvested units, attention to the construction of trail system approaches especially where the stream channel is more deeply incised and the channel itself is steeper can lead to sediment level reductions.

Though the design of this study makes it difficult to separate the effects of improved stream crossings, the establishment of an SMZ, and the retention of channel bank trees in reducing stream sediment levels (Witt, Barton et al. 2013), the result obtained from linear modeling that residual basal area of a harvested analysis unit is nearly significantly negatively related to turbidity suggests that an SMZ with at least some canopy retention may be an important factor in reducing stream sediment levels in the ephemeral channels under study here. Though Witt et al. (2013) hypothesized that sedimentation from stream crossings was most likely the main controlling factor in sediment levels, further analysis here shows that harvest equipment limitation and some canopy retention may also be noteworthy. A study design that explicitly separates the factors of improved stream crossings, SMZ establishment with harvest equipment limitation or exclusion, and canopy retention is needed to accurately identify the relative contributions of each of these factors.

The result that number of harvest machine traverses over stream crossings, when looking at the crossing types individually, is not significantly related to sediment levels is really only surprising in the instance of unimproved fords. One would think that every time a machine tracked through an unimproved ford crossing, significant sediment would be stirred up, and stream sediment levels would increase. In fact, Reeves (2008; 2012) found, during a study of these same four types of stream crossings, that stream sediment levels associated with trafficking over corrugated steel culverts were significantly greater than levels from the other crossing types. However, that study involved water sampling above and below the crossing locations immediately before and after each crossing traverse, while this study relied on an average of automatic water sampling data from well after crossing retirement. It is likely that any differences that could have been observed in this study were erased by the delay involved. Reeves (2008; 2012) also found that there were no differences among the three elevated crossing types (culvert/steel pipe, pipe bundle, and bridge) during use, and hypothesized that once these types of crossing were successfully installed, they were successful at preventing high levels of sediment introduction during machine traverses.

It is intriguing that a similar result was obtained in this stream crossing study as was seen in the sediment path study. Results here indicated that skidder traverses of stream crossings other than bridges may be related to decreased turbidity levels below the crossings, while feller-buncher traverses may be tied to increased turbidity. This is further support of the hypothesis that rubber-tired skidder traffic may actually compact the soil surface, leading to a reduced possibility of sediment delivery to the streams at the

crossings, while the tracks of the feller-buncher tend to churn the soil and make it available to be dislodged by precipitation and flow into the stream at or near the crossings.

This study showed that time investment for each of the improved crossing types is a factor in selection of the appropriate stream crossing method during forest harvest. Steel pipes and bridges were roughly similar in time investment, while unimproved fords and pipe bundles were also roughly similar. However, steel pipes and bridges took only around a quarter of the time that fords and pipe bundles took. Unimproved fords, with their major time investment (not to mention fuel and labor cost) for installation, removal, and retirement, and the fact that they were by far the worst in sediment production at the stream crossings (Reeves, Stringer et al. 2008; Reeves 2012; Witt, Barton et al. 2013), should not be recommended for a temporary stream crossing option.

In this study, since pipe bundles were a major investment in time (also fuel, labor, and materials cost), and were not any better than steel pipes and bridges at reducing stream sediment levels, they presented no advantages in solving the problem of temporary stream crossings during harvest operations. In fact, one of the pipe bundle crossings installed in this study required nearly 7 hours of total time for installation and crossing retirement, while the other two averaged only a little over 1 hour. All of the pipe bundles in this study were effectively destroyed upon removal as well, due to the volume of fill necessary to level the skid trail over them. This illustrates the fact that pipe bundles are difficult to use in very steep terrain where the channels to be crossed are deeply incised

and have a high channel slope, and a large volume of fill is required to level the trail over them. Though Reeves (2008; 2012) found that pipe bundles were the most efficient crossing type in terms of sediment prevented per dollar spent, that study was done on stream crossings where the channel slope was nearly level, and only a small volume of fill was required to cover the pipe bundle in the channel. That amount of fill was easily removed at pipe bundle crossing retirement by dragging of the pipe bundle out of the stream channel. However, in this study, due to the high channel slope of the streams crossed, it was very difficult for even highly experienced bulldozer operators to remove enough fill from atop the downstream end of the pipe bundle to enable efficient extraction. For this reason, it is recommended that pipe bundles not be used in stream channels with a slope of greater than 20 degrees or 35%.

Steel pipes and portable skidder bridges, then, are the two most viable options for stream crossings in the steeply sloping ground of the Cumberland Plateau, as they both drastically improve stream sediment levels compared to unimproved fords (Reeves, Stringer et al. 2008; Reeves 2012; Witt, Barton et al. 2013), and are a small time investment for installation, removal, and retirement. Steel pipes can be had at low cost, and are widely available to most loggers; their installation, removal, and retirement is second nature to many operators in the Cumberland Plateau. Portable skidder bridges could be made on site by many logging operators, as low grade but strong logs are readily available at most logging sites, and the threaded rod and hardware needed is relatively low cost and widely available. However, different studies have had divergent views of the cost of bridge use: Taylor et al. (1999) stated that bridges were the most expensive

stream crossing option, while Aust et al. (2003) found them to be low in cost. Either way, bridges are novel to many operators in the Cumberland Plateau at this point, but continued efforts to recommend them and demonstrate their use should make headway in making them more widely used. Also, though the results of this study do not show it directly as far as improvements in sediment reduction or in time savings, the more natural stream channel and banks left after retirement of a bridge crossing (figure 3.6) as compared to a steel pipe crossing from which much fill soil has had to be removed (figure 3.3) has advantages in the aesthetics left after a logging job. Aust et al. (2011) found that bridges are overall the least disruptive stream crossing option, and that steel pipe crossings, especially at their skid trail approaches, had higher potential erodibility than other crossing types. All of these factors taken together indicate that bridges should be promoted as a solution to temporary stream crossings during harvest operations.

Table 3.1—Stream crossings involved in this study, with type of crossing and number of traverses by harvest machine type.

Unit	Treatment	Crossing type	Skidder traverses	Bulldozer traverses	Feller-buncher traverses	Total number of traverses	Turbidity
North Shelly Rock	55ft-50%	unimproved ford	142	73	14	229	2.841
North Shelly Rock	55ft-50%	unimproved ford	44	72	17	133	2.687
North Shelly Rock	55ft-50%	unimproved ford	141	103	16	260	2.383
West Shelly Rock	110ft-100%	steel pipe	180	39	16	235	1.864
West Shelly Rock	110ft-100%	steel pipe	559	77	46	682	2.068
West Shelly Rock	110ft-100%	bridge	218	142	21	381	1.910
West Shelly Rock	110ft-100%	pipe bundle	228	26	9	263	1.916
South Shelly Rock	55ft-100%	steel pipe	89	7	8	104	2.162
South Shelly Rock	55ft-100%	pipe bundle	121	42	25	188	3.351
South Shelly Rock	55ft-100%	pipe bundle	541	126	56	723	2.057
South Shelly Rock	55ft-100%	bridge	99	18	47	164	2.175
South Shelly Rock	55ft-100%	bridge	174	32	53	259	1.856

Table 3.2—Results of pairwise multivariate analyses among independent variables used for modeling.

Independent variable	Correlated with	Value	Variable eliminated from modeling
Control analysis units			
Channel slope	Moisture index	0.8518	None eliminated
Channel slope	Average basal area	0.9260	All regressed individually
Average slope	Maximum slope	0.9333	
Average slope	Moisture index	0.9530	
Maximum slope	Moisture index	0.8046	
Trail density	Channel slope	0.7815	
Trail density	Moisture index	0.8205	
Harvested analysis units			
Maximum slope	Average slope	0.8382	Average slope
Moisture index	Average slope	0.7521	Average slope
Erosional surface area	Fill volume	0.9354	Erosional surface area
Erosional surface area	Maximum trail slope	0.7558	Erosional surface area

Table 3.3—Summary table of linear regressions for the controls, using log-transformed mean turbidity as the response variable.

Independent variable	Regression R^2	p value	Sign of relationship to response variable
Moisture index	0.838941	0.0841	+
Trail density	0.954185	0.0232	+

Table 3.4—Summary table of environmental, harvest operations, and stream crossing morphology linear models for the harvested units, using log-transformed mean turbidity as the response variable.

Independent variable	Model R ²	p value	Sign of relationship to response variable
Channel slope	0.480131	0.0665	+
Average basal area	0.262433	0.1168	-
Maximum trail slope	0.318637	0.1169	+

Table 3.5—Summary table of harvest machine traverses linear model for the harvested units, using log-transformed mean turbidity as the response variable, for all crossing types other than bridges. Model $R^2=0.582275$.

Independent variable	p value	Sign of relationship to response variable
Skidder traverses	0.0515	-
Feller-buncher traverses	0.1297	+
Bulldozer traverses	0.8860	-

Table 3.6—Approximate average stream crossing installation, removal, and retirement times.

Stream crossing type	Installation	Number observed	Removal and retirement	Number observed	Total time
Unimproved ford	00:31:50	1	00:36:28	2	01:08:18
Steel pipe	00:11:05	1	00:05:14	1	00:16:19
Pipe bundle	00:21:12	3	00:54:34	3	01:15:46
Bridge	00:12:17	3	00:11:03	2	00:23:20

Figure 3.1—A retired ford in Shelly Rock North (the 55ft-50% treatment). The majority of introduced soil has been removed, with the stream channel returned to its approximate contours.



Photo: Daniel Bowker

Figure 3.2—A culvert installed in a stream channel. This photo shows a corrugated metal culvert rather than the smaller diameter steel pipes used during SMZ study harvest operations.



Photo: Chris Reeves

Figure 3.3—Stream crossed by a steel pipe after retirement.



Photo: Daniel Bowker

Figure 3.4—Completed cant panel of a portable skidder bridge. Three similar panels were used for each bridge crossing.



Photo: Chris Reeves

Figure 3.5—Installed portable skidder bridge. The logging contractor was more comfortable using six cant panels for stream crossing during the SMZ study, as the eastern white pine did not seem strong enough to hold the weight of the harvesting equipment when using only one layer of three panels.



Photo: Daniel Bowker

Figure 3.6—Retired skidder bridge crossing.



Photo: Daniel Bowker

Figure 3.7—Drilling of PVC pipe for threading with steel cable. A finished pipe bundle can be seen in the background.



Photo: Chris Reeves

Figure 3.8—Pipe bundle installed in a stream channel, covered with geotextile.



Photo: Daniel Bowker

Figure 3.9—Stream channel crossed by installation of a PVC pipe bundle, after retirement.



Photo: Daniel Bowker

Figure 3.10—Map of the 55ft-100% treatment watershed in green, showing units subjected to experimental analysis in hatched orange. Perennial stream sections are in solid blue, intermittent sections are in dashed blue, and ephemeral stream sections are in hatched blue. The skid trail network is represented by black lines. The log landing area is at the high point at the northwest of the watershed, and is represented in gray.

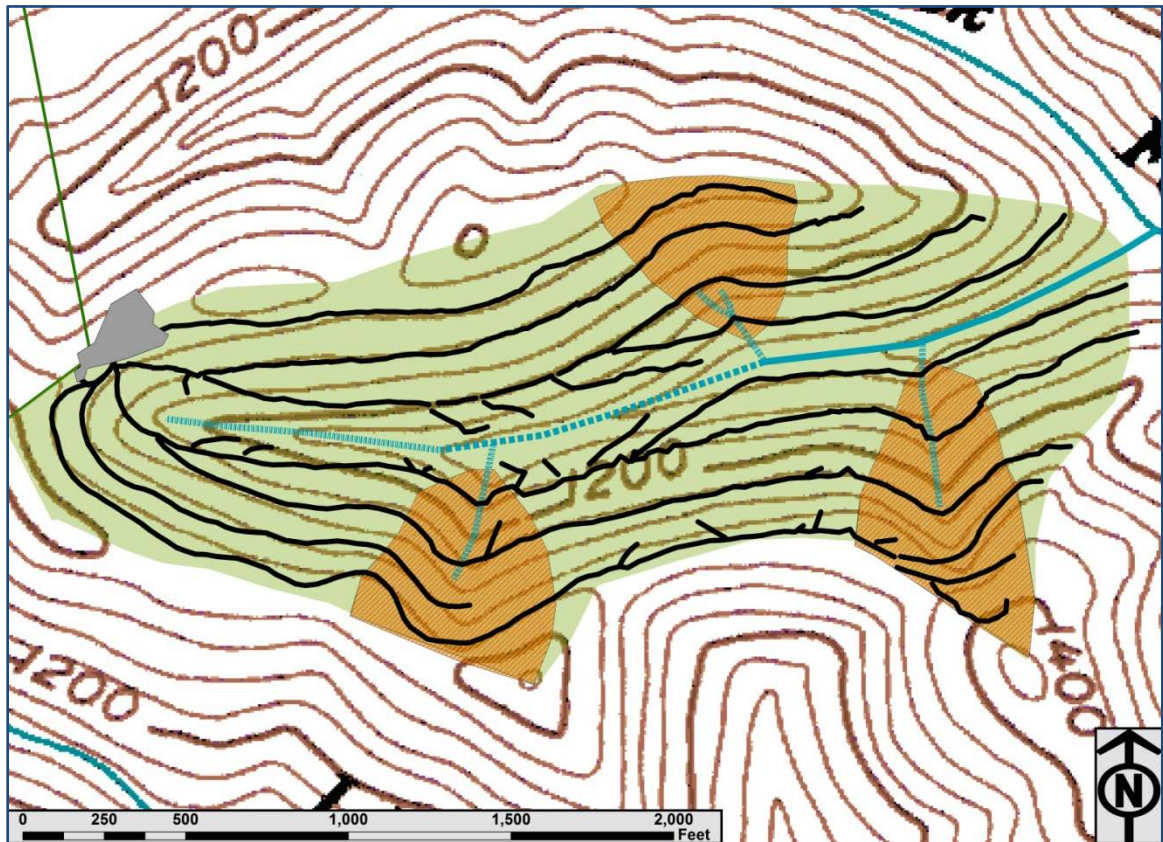


Figure 3.11—Map of an analysis unit in the 55ft-100% treatment watershed. Watershed is in green, and the analysis unit is in hatched orange. The section of perennial stream is in solid blue, the intermittent stream section is in dashed blue, and the ephemeral stream section is in hatched blue. The skid trail network is represented by black lines. Note the location where the skid trail network crosses the ephemeral channel. Water sampling occurred at the lower border of the orange unit, at the ephemeral stream.

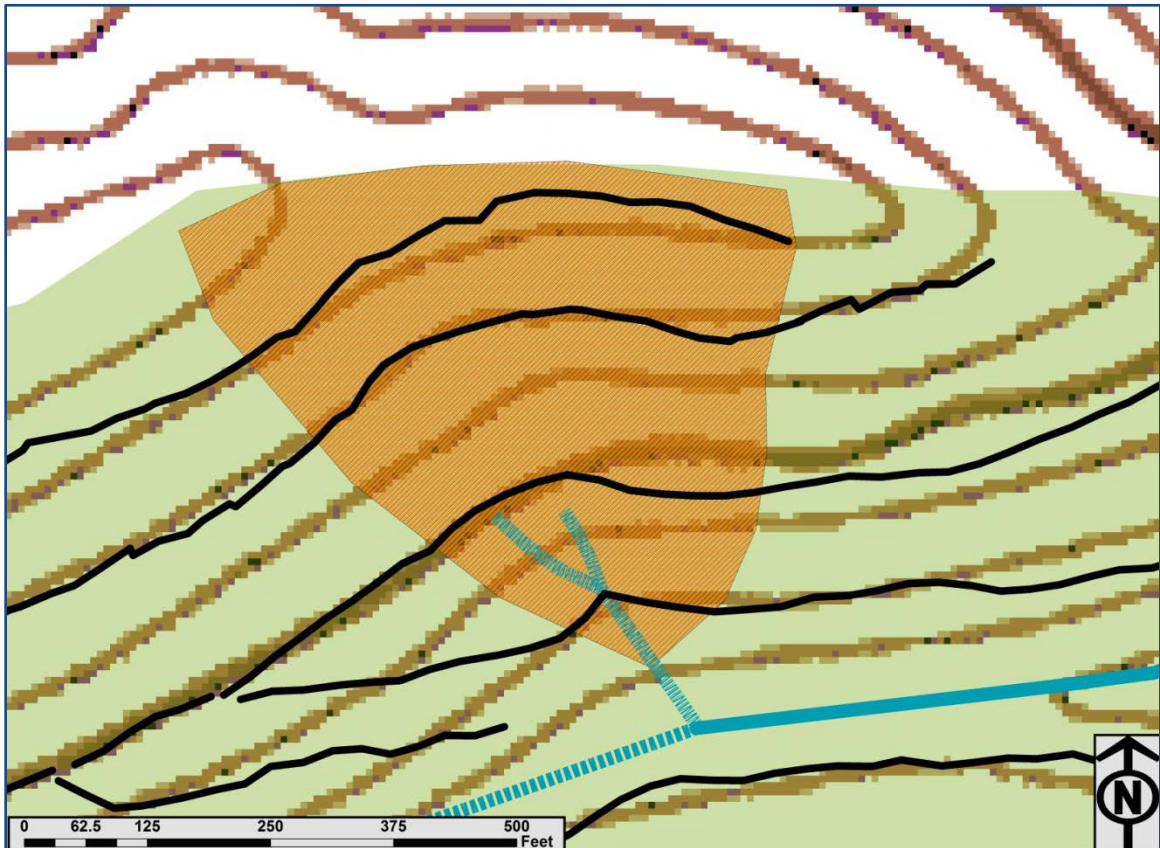


Figure 3.12—Screen shot from Google SketchUp showing a stream crossing in the 55ft-50% treatment as an example of the triangular prism created to model each stream crossing, in order to calculate approximate fill volume and erosional surface area after crossing retirement.

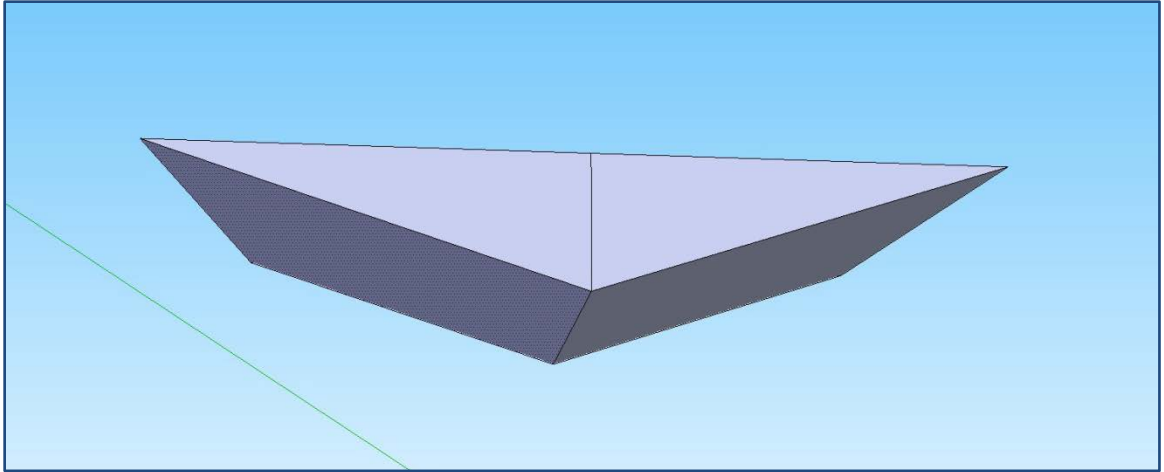


Figure 3.13—Map of 3 analysis units for the 55ft-50% treatment watershed North Shelly Rock. Analysis units are in hatched orange, skid trail network is in black, perennial stream sections are solid blue lines, intermittent stream sections are dashed blue lines, and ephemeral stream sections are hatched blue lines. Locations where stream sampling was conducted are shown as blue triangles.

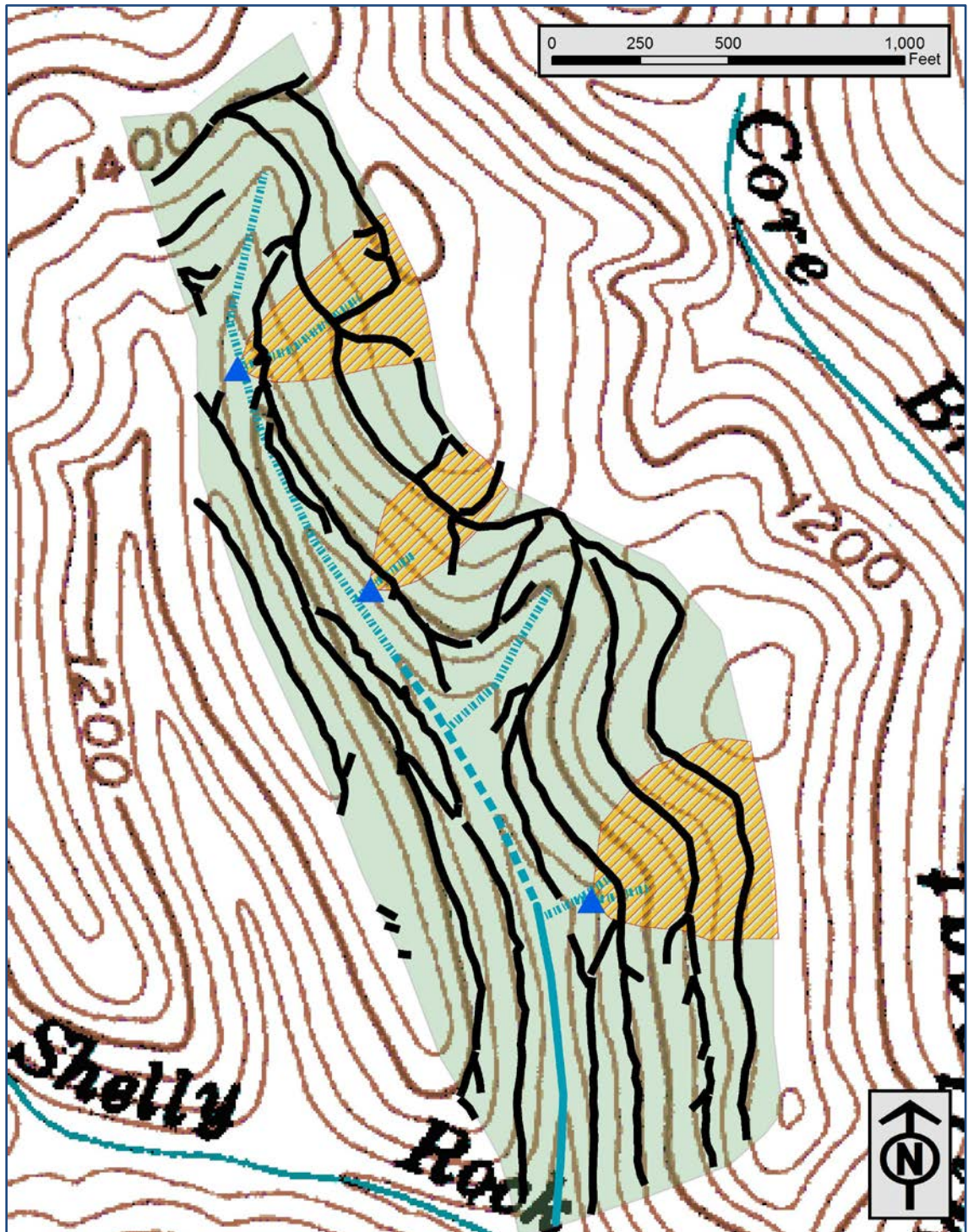


Figure 3.14—Map of 4 analysis units for the 110ft-100% treatment watershed West Shelly Rock. Analysis units are in hatched orange, skid trail network is in black, perennial stream sections are solid blue lines, intermittent stream sections are dashed blue lines, and ephemeral stream sections are hatched blue lines. Locations where stream sampling was conducted are shown as blue triangles.



Figure 3.15—Map of 3 analysis units for the 55ft-100% treatment watershed South Shelly Rock. Analysis units are in hatched orange, skid trail network is in black, perennial stream sections are solid blue lines, intermittent stream sections are dashed blue lines, and ephemeral stream sections are hatched blue lines. Locations where stream sampling was conducted are shown as blue triangles.

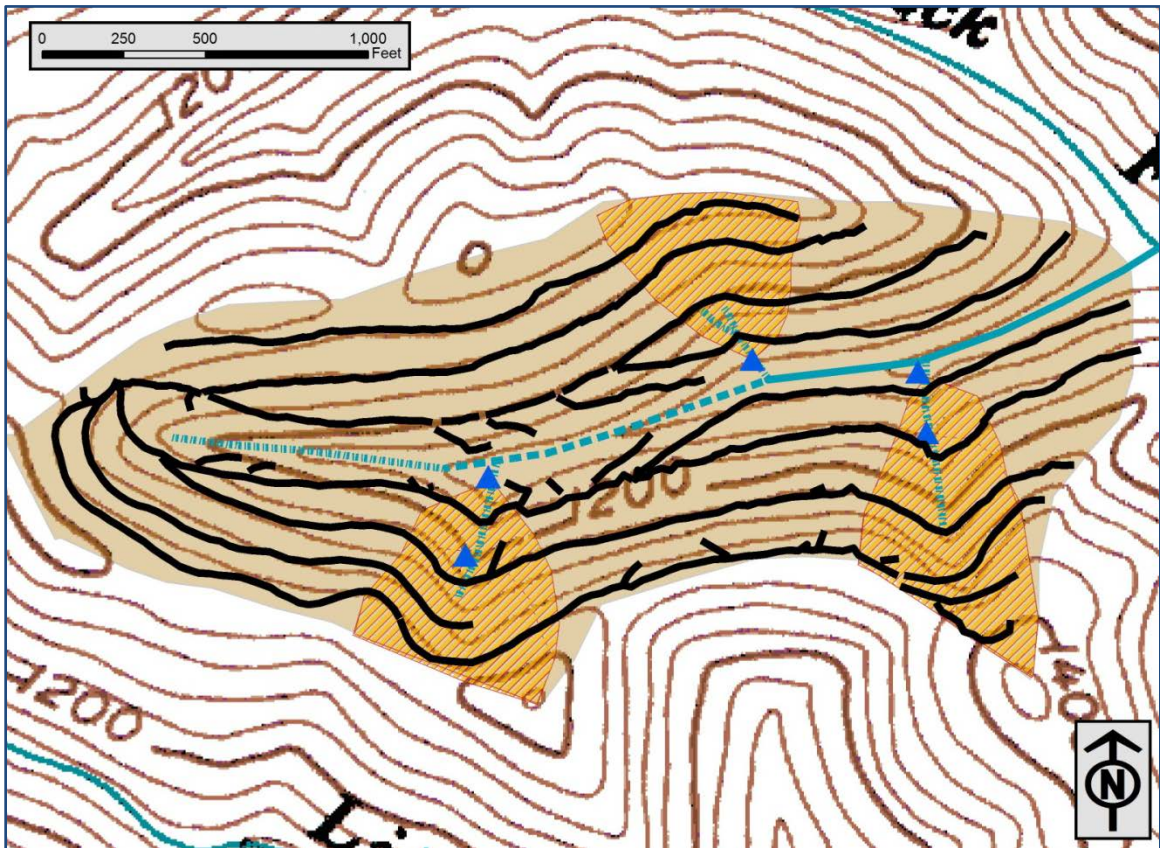


Figure 3.16—Map of 2 analysis units for control watershed Little Millseat. Analysis units are in hatched orange, skid trail network is in black, perennial stream sections are solid blue lines, intermittent stream sections are dashed blue lines, and ephemeral stream sections are hatched blue lines. Locations where stream sampling was conducted are shown as blue triangles.

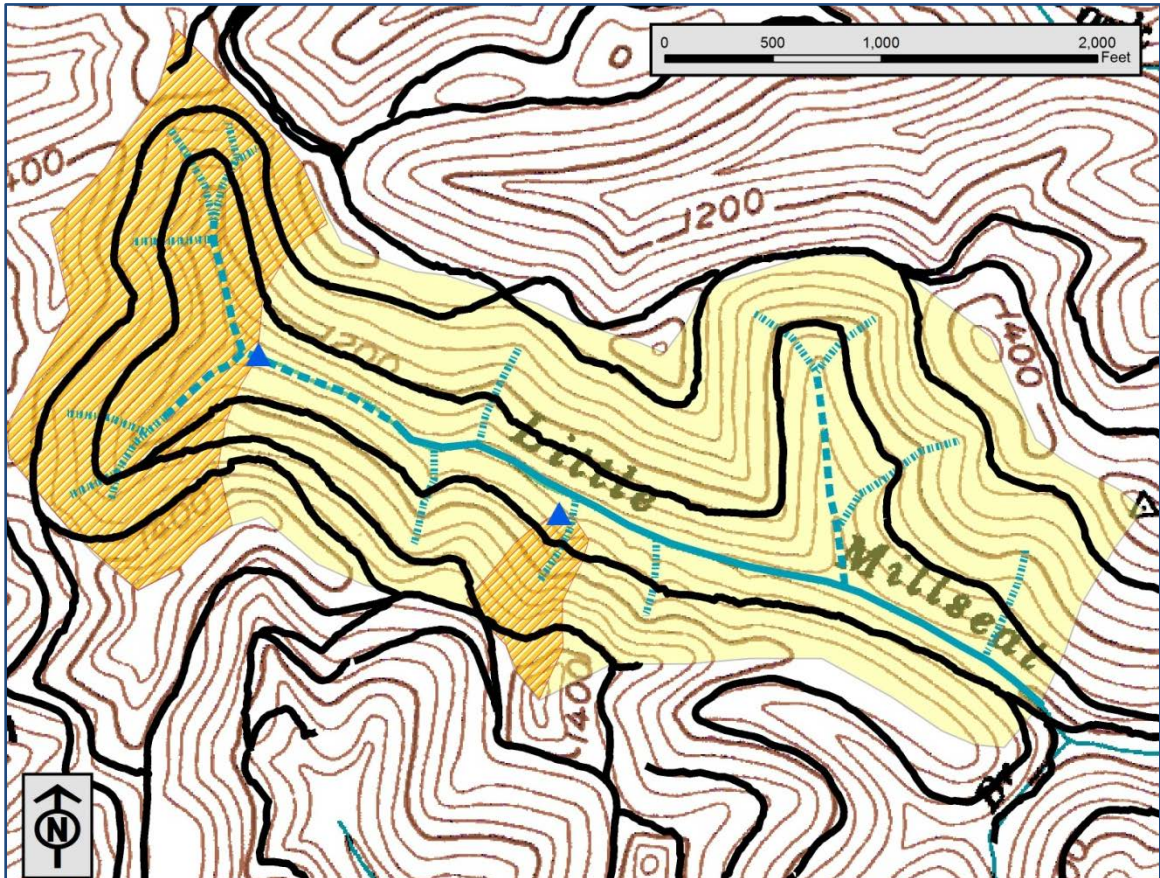


Figure 3.17—Map of 2 analysis units for control watershed Falling Rock. Analysis units are in hatched orange, skid trail network is in black, perennial stream sections are solid blue lines, intermittent stream sections are dashed blue lines, and ephemeral stream sections are hatched blue lines. Locations where stream sampling was conducted are shown as blue triangles.

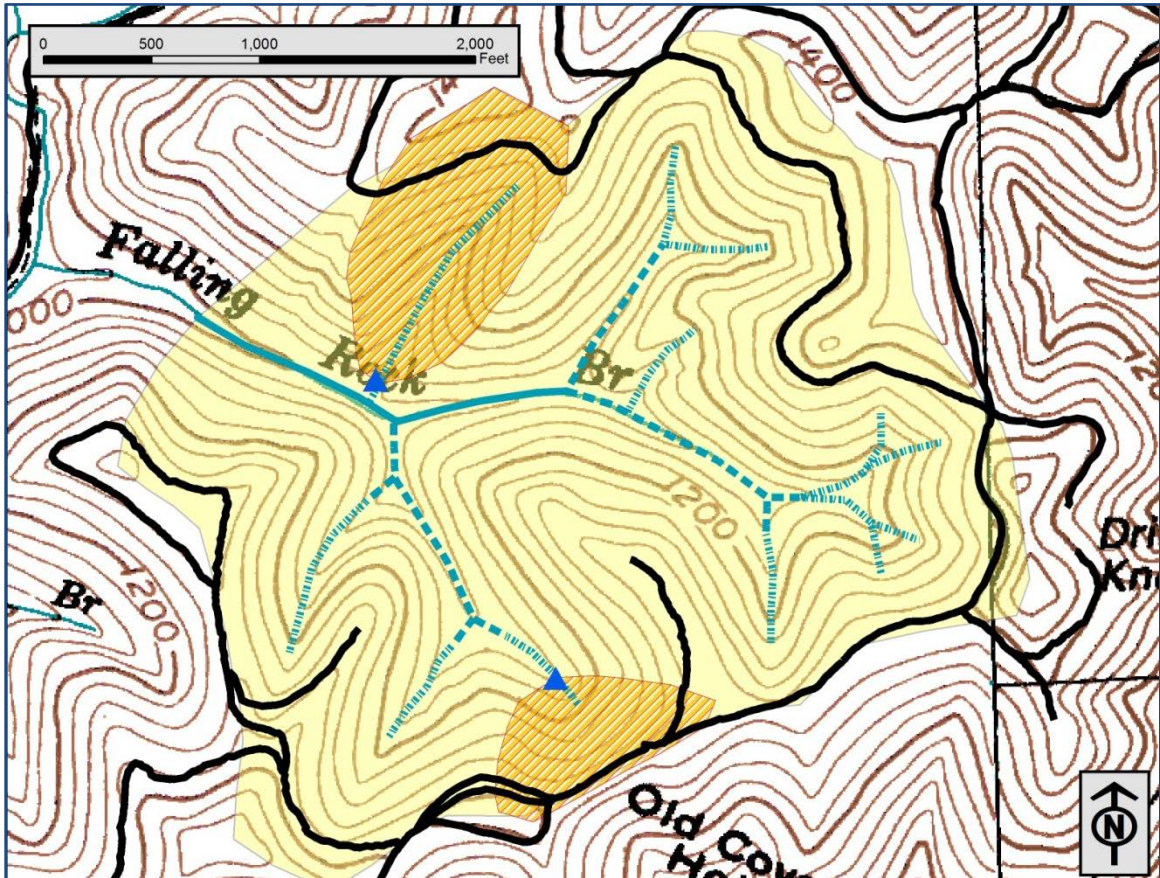


Figure 3.18—Map of 2 stream crossings for the 110ft-100% treatment watershed Wet Fork. Perennial stream sections are solid blue lines, intermittent stream sections are dashed blue lines, and ephemeral stream sections are hatched blue lines. Locations where stream sampling was conducted are shown as blue triangles.

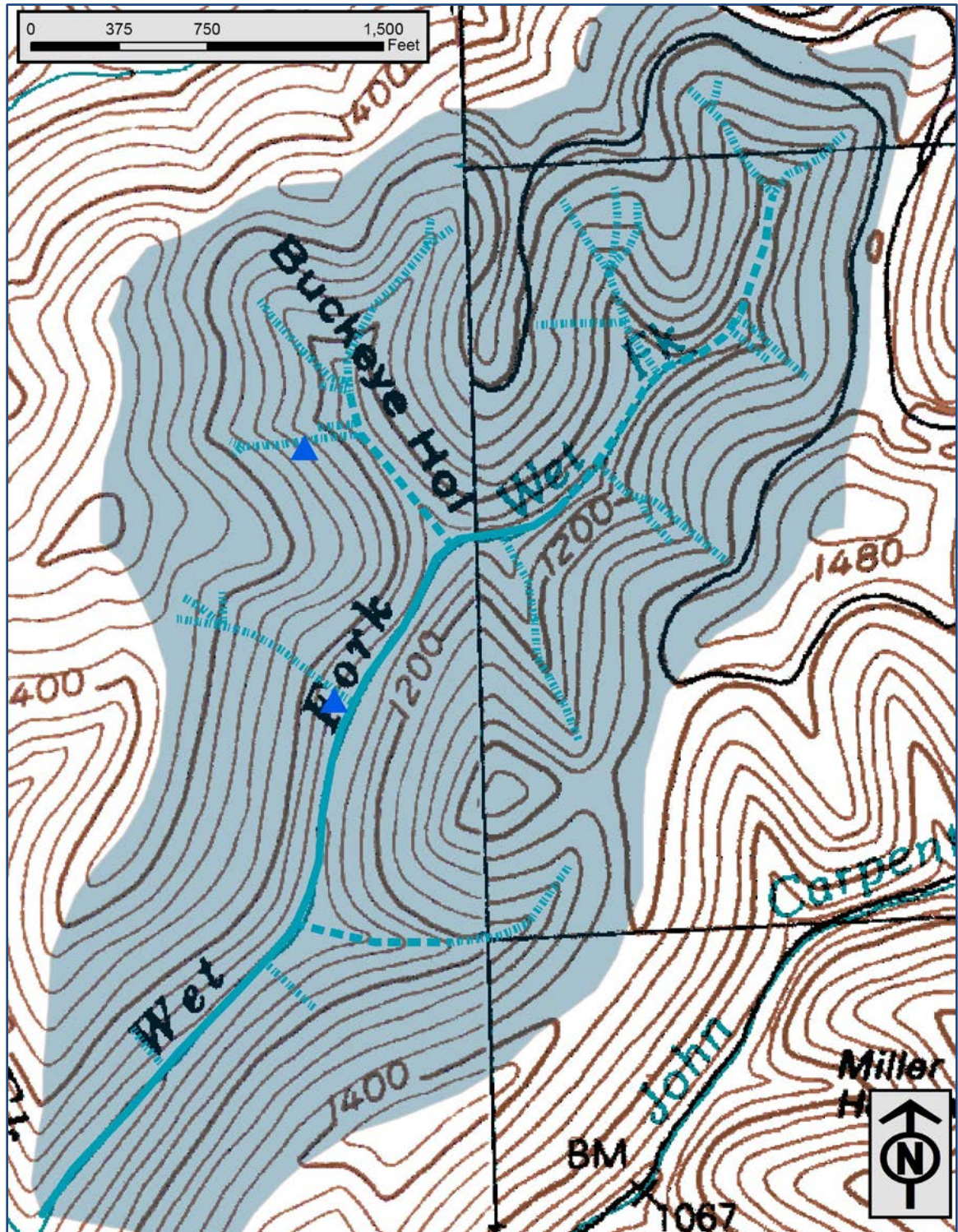
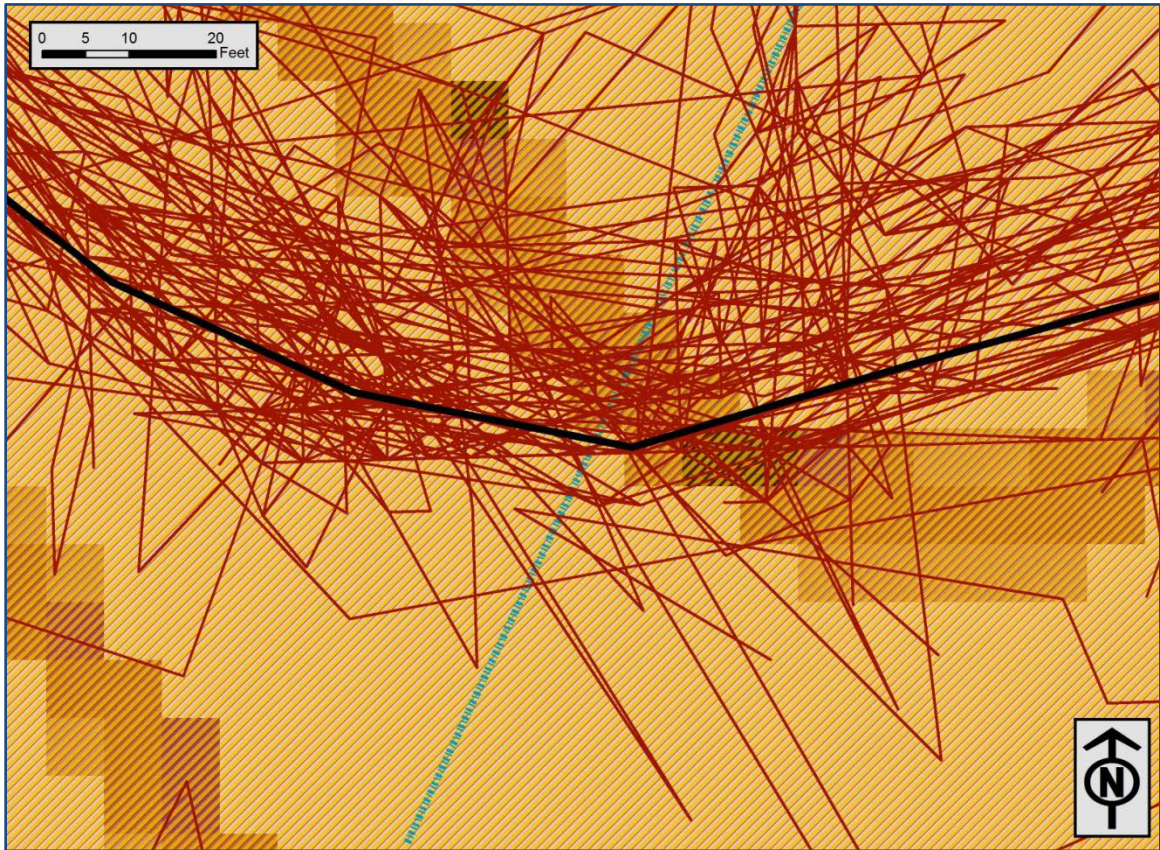


Figure 3.19—Example map showing line shapefile output of GPS data of harvest equipment traversing a stream crossing location. The ephemeral stream section is represented by the hatched blue line, while the skid trail crossing this stream is shown as a solid black line. The red lines connect consecutive GPS positions obtained from the MultiDAT datalogger aboard a bulldozer.



CHAPTER IV: SUMMARY AND MANAGEMENT IMPLICATIONS

IV.1. SMZ buffer width and canopy retention

The results of the two studies detailed here indicate that increasing the SMZ buffer width mandated by Kentucky forest practice regulations would decrease sediment delivery to the stream network during forest harvest. Increased buffer width helped prevent sediment paths in intermittent and perennial channels, and was significantly negatively related to the number and width of undisturbed and total sediment paths reaching the stream network. An SMZ buffer on ephemeral channels also reduced the number and width of total sediment paths. Also, as the minimum distance from the trail network to the stream increased, the number and width of machine-caused sediment paths decreased. Though no significant effect on reducing sediment delivery to ephemeral channels at stream crossings by establishing a forested buffer strip on those channels was shown in these studies, establishing an SMZ for ephemeral channels would have positive effects on stream temperature, help maintain coarse woody debris inputs, and retain natural habitat characteristics important to the functioning of these ephemeral channels (Witt, Barton et al. 2013).

Increased canopy retention was shown to be a factor in reducing stream sedimentation by these studies as well, most likely by reducing the amount of harvesting activity near the stream. Greater canopy retention was associated with a reduced number of machine-caused sediment paths in intermittent channels, and though not significant, was trending toward association with decreased sediment delivery at the ephemeral channel stream crossings.

For these reasons, a reasonable modification to Kentucky's forest practice guidelines for commercial harvesting would be to increase SMZ buffer width along perennial and intermittent stream channels, establish an SMZ equipment limitation buffer along ephemeral channels, and mandate the retention of a minimal amount of canopy along ephemeral channels where retention is not currently required, such as the trees along the channel banks. The exact amount of increased SMZ buffer width would need to be debated among the various stakeholder groups; however, this study shows that any increase is likely to benefit the water quality of the area harvested. Further study could investigate the actual revenue lost by modest increases in perennial and intermittent stream channel SMZ widths, and by the retention of channel bank trees in the ephemeral channels.

IV.2. Skid trail system and forest harvest equipment traffic

These studies show the importance that careful skid trail system construction, maintenance, and retirement have in protecting water quality in harvested areas. Increased trail density in the unharvested controls was related to increased turbidity levels, and can reasonably be expected to be shown to be related to increased turbidity levels in harvested areas as well with more detailed study. Also, all of the machine-caused sediment paths observed in this study originated from water control structures put in place during retirement of the skid trail system, with those placed at low points of the skid trail network especially prone to play a role in sediment path initiation. For these reasons, logger training sessions conducted in Kentucky should place increased emphasis on planning and construction of skid trail networks in order to decrease the density of

trails necessary to efficiently harvest the timber in an area, and the retirement of skid trails with properly cited and effectively constructed water control structures should be made a special priority.

An unexpected but intriguing finding of these studies is that wheeled, rubber-tired skidder traffic may decrease the potential for erosion of soil into the stream network, while tracked equipment traffic may increase this potential. Though more research into these mechanisms is needed before mandating changes in the amount of allowable traffic by different types of harvest equipment, it would be reasonable to mention this finding during operator training sessions, and to recommend that tracked equipment be used as sparingly as possible for efficient harvesting. For example, the use of bulldozers for skidding logs short distances is common practice on the Cumberland Plateau, as bulldozers are usually working along the steeper lower slopes near stream channels with chainsaw hand crews. Replacing some of these bulldozer trips with skidder pulls may be advisable to decrease potential for sediment delivery to streams.

IV.3. Stream crossings

The results of the stream crossing study reported above make it clear that mandating the use of improved stream crossings during harvest operations is a priority. Unimproved fords have such dramatic effects on stream sedimentation that they should be phased out entirely as an acceptable method of crossing streams during forest harvest. Logger training sessions should emphasize the negative water quality effects of unimproved fords, as well as highlight the fact that the time investment in installing, removing, and

retiring fords is much greater than more effective methods such as steel pipes and bridges. The sediment reduction, time savings, and aesthetic advantages of bridge crossings should be greatly emphasized, and training sessions should demonstrate the ease of their construction and use. Steel pipes should be considered a stream crossing method with the advantages of ease of use and relatively low cost, but should only be used where the removal of fill is straightforward and where channel flows are expected to be relatively low. Though not directly shown by this study, deep channels with a large volume of fill needed to level the skid trail over the steel pipe, as well as areas with high volume flows, have potential for greater sediment delivery to streams than bridges (Aust, Carroll et al. 2011). Finally, as degree of channel slope and degree of slope of skid trail approaches to stream crossings were shown to be positively related to turbidity levels, the proper citing and construction of any method of crossing a stream channel should be emphasized. If a particular stream channel is too deep or too steep to cross without a major construction effort, the possibility of rerouting the trail network around the head of that channel should be highlighted.

IV.4 Environmental factors

As the aspect of a particular area was shown to be related to greater potential sediment delivery to the stream network, emphasis should be placed on paying attention to aspect and potential moisture level of the site before constructing the trail network.

Discouraging harvesting of wetter sites is not feasible, as the wetter (more northeasterly) aspects are generally the more productive sites in the Cumberland Plateau and have a greater volume of higher quality timber. However, emphasizing to operators that better

timber most likely means wetter soil and hence a greater potential of sediment delivery to the stream network may help them to more carefully construct and retire the trail network across these wetter sites.

Finally, the importance of surface roughness in preventing sediment delivery to streams should be highlighted during logger training sessions. Anecdotally, it has been observed that some in the regulatory community do not recognize that the tops and branches of hardwood timber have a preventative effect on stream sedimentation. The evidence uncovered here that surface roughness, especially coarse branch surface roughness, is related to fewer and narrower sediment paths may help to counter this belief. Swift (1986) also found that increased surface roughness in the form of brush barriers of logging slash placed downslope from the skid trail system reduced the transport distance of sediment, and stated that the filter strip width could even be reduced where these brush barriers are used. Recommending that operators leave significant levels of slash below skid trails along the edges of SMZs may be worthwhile, though the prohibition on blocking the stream channel with logging slash must be maintained.

REFERENCES

- Arthur, M. A., G. B. Coltharp and D. L. Brown (1998). "Effects of best management practices on forest streamwater quality in eastern Kentucky." Journal of the American Water Resources Association **34**(3): 481-495.
- Aust, W. M. and C. R. Blinn (2004). "Forestry best management practices for timber harvesting and site preparation in the Eastern United States: an overview of water quality and productivity research during the past 20 years." Water, Air, and Soil Pollution: Focus **4**: 5-36.
- Aust, W. M., M. B. Carroll, M. C. Bolding and C. A. Dolloff (2011). "Operational forest stream crossings effects on water quality in the Virginia Piedmont." Southern Journal of Applied Forestry **35**(3): 123-130.
- Aust, W. M., R. Visser, T. Gallagher, T. Roberts and M. Poirot (2003). "Cost of six different stream crossing options in the Appalachian area." Southern Journal of Applied Forestry **27**(1): 66-70.
- Beers, T. W., P. E. Dress and L. C. Wensel (1966). "Aspect transformation in site productivity research." Journal of Forestry **64**(10): 691-692.
- Benda, L., M. A. Hassan, M. Church and C. L. May (2005). "Geomorphology of steep-land headwaters: the transition from hillslopes to channels." Journal of the American Water Resources Association **41**(4): 835-851.
- Binkley, D. and T. C. Brown (1993). "Forest practices as nonpoint sources of pollution in North America." Water Resources Bulletin **29**(5): 729-740.
- Blinn, C. R. and M. A. Kilgore (2001). "Riparian management practices, a summary of state guidelines." Journal of Forestry **99**(8): 11-17.
- Brooks, K. N., P. F. Ffolliott, H. N. Gregersen and L. F. DeBano (2003). Hydrology and the management of watersheds. Ames, Iowa, Iowa State Press.
- Carter, E. A., T. P. McDonald and J. L. Torbert (1999). Application of GPS technology to monitor traffic intensity and soil impacts in a forest harvest operation. Proceedings of the Tenth Biennial Southern Silvicultural Research Conference. Shreveport, LA, USDA Forest Service Southern Research Station. **GTR-SRS-30**.
- Corbett, E. S., J. A. Lynch and W. E. Sopper (1978). "Timber harvesting practices and water quality in the eastern United States." Journal of Forestry **76**(8): 484-488.
- Corner, R. A., J. H. Bassman and B. C. Moore (1996). "Monitoring timber harvest impacts on stream sedimentation: instream vs. upslope methods." Western Journal of Applied Forestry **11**(1): 25-32.
- Croke, J. C. and P. B. Hairsine (2006). "Sediment delivery in managed forests: a review." Environmental Reviews **14**(1): 59-87.
- Davis, C. T. and L. D. Kellogg (2005). Measuring machine productivity with the MultiDat datalogger: a demonstration on three forest machines. Council on Forest Engineering Conference Proceedings.
- Deckert, C. J. and P. V. Bolstad (1996). "Global positioning system (GPS) accuracies in eastern U.S. deciduous and conifer forests." Southern Journal of Applied Forestry **20**(2): 81-84.
- Dickinson, T. M. (1992). Economic analysis of streamside management zones. Forestry. Lexington, Kentucky, University of Kentucky. **Master of Science**.

- Edwards, P. J. and K. W. J. Williard (2010). "Efficiencies of forestry best management practices for reducing sediment and nutrient losses in the eastern United States." Journal of Forestry **108**: 245-249.
- Ellefson, P. V. and P. D. Miles (1985). "Protecting water quality in the Midwest: impact on timber harvesting costs." Northern Journal of Applied Forestry **2**(2): 57-61.
- Fritz, K. M., B. R. Johnson and D. M. Walters (2008). "Physical indicators of hydrologic permanence in forested headwater streams." Journal of the North American Benthological Society **27**(3): 690-704.
- Germain, R. H. and J. F. Munsell (2005). "How much land is needed for the harvest access system on nonindustrial private forestlands dominated by northern hardwoods?" Northern Journal of Applied Forestry **22**(4): 243-247.
- Grayson, R. B., S. R. Haydon, M. D. A. Jayasuriya and B. L. Finlayson (1993). "Water quality in mountain ash forests--separating the impacts of roads from those of logging operations." Journal of Hydrology **150**(2-4): 459-480.
- Hairsine, P. B., J. C. Croke, H. Mathews, P. Fogarty and S. P. Mockler (2002). "Modelling plumes of overland flow from logging tracks." Hydrological Processes **16**(12): 2311-2327.
- Harmon, M. E. and J. Sexton (1996). Guidelines for measurements of woody detritus in forest ecosystems, US LTER Network Office Seattle (WA).
- Karwan, D. L., J. A. Gravelle and J. A. Hubbart (2007). "Effects of timber harvest on suspended sediment loads in Mica Creek, Idaho." Forest Science **53**: 181-188.
- Kentucky Division of Geographic Information. (2006, July 24, 2006). "Geospatial data." Retrieved January 1, 2006, from <http://gis.ky.gov/gisdata.htm>.
- Ketcheson, G. L., W. F. Megahan and J. G. King (1999). "'R1-R4' and 'BOISED' sediment prediction model tests using forest roads in granitics." Journal of the American Water Resources Association **35**(1): 83-98.
- Kochenderfer, J. N. and P. J. Edwards (1990). Effectiveness of three streamside management practices in the Central Appalachians. Proceedings of the Sixth Biennial Southern Silvicultural Research Conference. Memphis, TN: 688-700.
- Kochenderfer, J. N., P. J. Edwards and F. Wood (1997). "Hydrologic impacts of logging an Appalachian watershed using West Virginia's best management practices." Northern Journal of Applied Forestry **14**(4): 207-218.
- Kreutzweiser, D. P. and S. S. Capell (2001). "Fine sediment deposition in streams after selective forest harvesting without riparian buffers." Canadian Journal of Forest Research **31**(12): 2134-2142.
- Lakel, W. A., W. M. Aust, M. C. Bolding, C. A. Dolloff, P. Keyser and R. Feldt (2010). "Sediment trapping by streamside management zones of various widths after forest harvest and site preparation." Forest Science **56**: 541-551.
- Lakel, W. A., W. M. Aust, C. A. Dolloff and A. W. Easterbrook (2006). Soil erosion from harvested sites versus streamside management zone sediment deposition in the Piedmont of Virginia. Proceedings of the 13th Biennial Southern Silvicultural Research Conference. K. F. Connor, Asheville, NC: USDA Forest Service Southern Research Station. **GTR-SRS-92**: 400-401.
- Lane, P. N. J. and G. J. Sheridan (2002). "Impact of an unsealed forest road stream crossing: water quality and sediment sources." Hydrological Processes **16**(13): 2599-2612.

- LeDoux, C. B. and E. Wilkerson (2006). A case study assessing opportunity costs and ecological benefits of streamside management zones and logging systems for eastern hardwood forests, Newtown Square, PA: USDA Forest Service Northern Research Station. **Research paper NRS-1.**
- Litschert, S. E. and L. H. MacDonald (2009). "Frequency and characteristics of sediment delivery pathways from forest harvest units to streams." Forest Ecology and Management **259**(2): 143-150.
- MacDonald, L. H. and D. Coe (2007). "Influence of headwater streams on downstream reaches in forested areas." Forest Science **53**: 148-168.
- Martin, C. W. and J. W. Hornbeck (1994). Sediment yields from undisturbed and intensively harvested northern hardwood forests. Proceedings of the 22nd Annual Hardwood Symposium of the Hardwood Research Council. **22**: 69-79.
- Mason, L. and J. E. Moll (1995). Pipe bundle and pipe mat stream crossings. San Dimas, CA, U.S. Department of Agriculture Forest Service: 4.
- May, C. (2007). "Sediment and wood routing in steep headwater streams: an overview of geomorphic processes and their topographic signatures." Forest Science **53**: 119-130.
- McDonald, T. P., E. A. Carter and S. E. Taylor (2002). "Using the global positioning system to map disturbance patterns of forest harvesting machinery." Canadian Journal of Forest Research **32**: 310-319.
- Michels, O. (2009). GPS and GIS application and analysis of timber harvesting operations on steep terrain. School of Forestry and Wildlife Sciences. Auburn, Alabama, Auburn University. **Master of Science.**
- Miller, W. L. and H. W. Everett (1975). "The economic impact of controlling nonpoint pollution in hardwood forest land." American Journal of Agricultural Economics **57**(4): 576-583.
- National Weather Service. (2012). "Annual climatological report for Jackson, Kentucky." Retrieved February 15, 2012, from www.nws.noaa.gov/climate/getclimate.php?wfo=jkl.
- Overstreet, J. C. (1984). Robinson Forest Inventory 1980-1982. Lexington, KY, University of Kentucky College of Agriculture, Department of Forestry.
- Rashin, E. B., C. J. Clishe, A. T. Loch and J. M. Bell (2006). "Effectiveness of timber harvest practices for controlling sediment related water quality impacts." Journal of the American Water Resources Association **42**(5): 1307-1327.
- Reeves, C. (2012). Effectiveness of elevated skid trail headwater stream crossings in the Cumberland Plateau. Forestry. Lexington, KY, University of Kentucky. **Master of Science.**
- Reeves, C., J. Stringer, C. Barton and C. Agouridis (2008). Sedimentation rates of temporary skid trail headwater stream crossings. 31st Annual meeting of the Council on Forest Engineering, Charleston, South Carolina, COFE.
- Richardson, J. S. and R. J. Danehy (2007). "A synthesis of the ecology of headwater streams and their riparian zones in temperate forests." Forest Science **53**: 131-147.
- Rivenbark, B. L. and C. R. Jackson (2004). "Concentrated flow breakthroughs moving through silvicultural streamside management zones: Southeastern piedmont, USA." Journal of the American Water Resources Association **40**(4): 1043-1052.

- Sheridan, G. J. and P. J. Noske (2007). "Catchment-scale contribution of forest roads to stream exports of sediment, phosphorus and nitrogen." Hydrological Processes **21**(23): 3107-3122.
- Stringer, J., L. Lowe, M. F. Smidt and C. Perkins (1998). Field guide to best management practices for timber harvesting in Kentucky, University of Kentucky, Cooperative Extension Service, Department of Forestry.
- Stringer, J. and C. Perkins (2001). Kentucky forest practice guidelines for water quality management, University of Kentucky, Cooperative Extension Service, Department of Forestry.
- Stringer, J. and A. Thompson (2000). "Comparison of forestry best management practices. Part 1: Streamside management zones." Forest Landowner **59**: 22-27.
- Stuart, G. W. and P. J. Edwards (2006). "Concepts about forests and water." Northern Journal of Applied Forestry **23**(1): 11-19.
- Stuart, W. B. and J. L. Carr (1991). Harvesting impacts on steep slopes in Virginia, Newton Square, PA: USDA Forest Service Northeastern Experiment Station. **GTR-NE-148**: 67-81.
- Summer, W. B., C. Rhett Jackson, D. Jones and M. Miwa (2006). Dry Creek long-term watershed study: effects of timber harvest on hydrology and sediment export in headwater streams in southwest Georgia. Proceedings of the 13th Biennial Southern Silvicultural Research Conference. K. F. Connor, Asheville, NC: USDA Forest Service Southern Research Station. **GTR-SRS-92**: 387-391.
- Swank, W. T., J. M. Vose and K. J. Elliott (2001). "Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment." Forest Ecology and Management **143**(1/3): 163-178.
- Swift, L. W. (1986). "Filter strip widths for forest roads in the southern Appalachians." Southern Journal of Applied Forestry **10**(1): 27-34.
- Swift, L. W. J. (1988). Forest access roads: design, maintenance, and soil loss. Forest Hydrology and Ecology at Coweeta. W. T. Swank and D. A. Crossley. New York, Springer-Verlag: 313-324.
- Taylor, S. E., T. P. McDonald, M. W. Veal and T. E. Grift (2001). Using GPS to evaluate productivity and performance of forest machine systems. First International Precision Forestry Symposium, Seattle, WA.
- Taylor, S. E., R. B. Rummer, K. H. Yoo, R. A. Welch and J. D. Thompson (1999). "What we know - and don't know - about water quality at stream crossings." Journal of Forestry **97**(8): 12-17.
- Terrell, S. B. (2008). Hydrologic and sediment transport responses to forest harvest and site preparation in headwater streams: South Georgia, USA. Warnell School of Forestry and Natural Resources. Athens, Georgia, University of Georgia. **Master of Science**.
- Trimble, G. R. and R. S. Sartz (1957). "How far from a stream should a logging road be located?" Journal of Forestry **55**: 339-341.
- U.S. Department of Agriculture Natural Resources Conservation Service. (2009). "Soil Survey Geographic (SSURGO) database for Breathitt County, Kentucky " Retrieved April 27, 2010, from <http://SoilDataMart.nrcs.usda.gov/>.

- Veal, M. W., S. E. Taylor, T. P. McDonald, D. K. McLemore and M. R. Dunn (2001). "Accuracy of tracking forest machines with GPS." Transactions of the ASAE **44**(6): 1903-1911.
- Wang, J. X., C. Long, J. McNeel and J. Baumgras (2004). "Productivity and cost of manual felling and cable skidding in central Appalachian hardwood forests." Forest Products Journal **54**(12): 45-51.
- Ward, J. M. and C. R. Jackson (2004). "Sediment trapping within forestry streamside management zones: Georgia Piedmont, USA." Journal of the American Water Resources Association **40**(6): 1421-1431.
- White, W. J., C. R. Jackson, L. T. West, L. A. Morris and A. P. Pinho (2007). "Sediment retention by forested filter strips in the Piedmont of Georgia." Journal of Soil and Water Conservation **62**(6): 453-463.
- Witt, E., C. Barton, J. Stringer, D. Bowker and R. Kolka (2013). "Evaluating best management practices for ephemeral stream protection following forest harvest in the Cumberland Plateau." Southern Journal of Applied Forestry **37**(1): 36-44.
- Wynn, T. M., S. Mostaghimi, J. W. Frazee, P. W. McClellan, R. M. Shaffer and W. M. Aust (2000). "Effects of forest harvesting best management practices on surface water quality in the Virginia coastal plain." Transactions of the ASAE **43**(4): 927-936.

VITA

Author's name: Daniel Whiteside Bowker

Birthplace: Danville, Kentucky

Education:

Bachelor of Arts, Rhodes College, Memphis, Tennessee, 1995

Master of Arts, University of Kentucky, Lexington, Kentucky, 1999

Bachelor of Science in Forestry, University of Kentucky, Lexington, Kentucky 2005

Professional positions:

Management Forester, University of Kentucky Robinson Forest, 2006-2010

Professional publications:

Witt, E., C. Barton, J. Stringer, D. Bowker and R. Kolka (2013). "Evaluating best management practices for ephemeral stream protection following forest harvest in the Cumberland Plateau." Southern Journal of Applied Forestry **37**(1): 36-44.

Elder, K., I. Angutikjuak, J. Baker, M. Belford, T. Bennett, K. Birkeland, D. Bowker, D. Chabot, A. Cheuvront, M. Dixon, D. Elder, L. Elder, S. Gearheard, G. Giedt, K. Grant, S. Green, E. Greene, N. Houfek, C. Huntington, H. Huntington, T. Huntington, D. Janigian, C. Johnson, G. Liston, R. Maris, A. Marsh, H.P. Marshall, Aidan Meiners, Alex Meiners, T. Meiners, L. Palluq, J. Pope, E. Qillaq, J. Sanguya, S. Sehnert, R. Simenhois, B. Starr, and R. Tyler. (In press). "Meteorological tower design for severe weather and remote locations." International Snow Science Workshop 2012.

Bowker, D. and J. Stringer (2010). "Efficacy of herbicide treatments for controlling residual sprouting of tree-of-heaven." In: Fei, S., J. Lhotka, J. Stringer, K. Gottschalk, G. Miller eds. Proceedings, 17th Central Hardwood Forest Conference. USDA Forest Service, Northern Research Station, Newtown Square, PA. General Technical Report NRS-P-78. [CD]

Bowker, D., J. Stringer, C. Barton, and S. Fei (2010). "GPS and GIS analysis of mobile harvesting equipment and sediment delivery to streams during forest harvest operations on steep terrain." In: Mitchell, D. and T. Gallagher eds. Proceedings of the 33rd Annual Meeting of the Council on Forest Engineering: Fueling the Future. [CD]

Bowker, D., J. Stringer, C. Barton, and S. Fei (2010). "GPS and GIS analysis of mobile harvesting equipment and sediment delivery to streams during forest harvest operations on steep terrain – experimental design." Extended poster abstract. In: Fei, S., J. Lhotka, J. Stringer, K. Gottschalk, G. Miller eds. Proceedings, 17th Central Hardwood Forest Conference. USDA Forest Service, Northern Research Station, Newtown Square, PA. General Technical Report NRS-P-78. [CD]

- Witt, E., C. Barton, J. Stringer, D. Bowker and R. Kolka (2010). "Evaluating best management practices for ephemeral channel protection following forest harvest in the Cumberland Plateau – preliminary findings." In: Fei, S., J. Lhotka, J. Stringer, K. Gottschalk, G. Miller eds. Proceedings, 17th Central Hardwood Forest Conference. USDA Forest Service, Northern Research Station, Newtown Square, PA. General Technical Report NRS-P-78. [CD]
- Witt, E., C. Barton, J. Stringer, D. Bowker and R. Kolka (2009). "Evaluating best management practices for ephemeral channel protection following forest harvest in the Cumberland Plateau – preliminary findings." American Society of Agricultural and Biological Engineers Paper No. 095840. St. Joseph, Mich.: ASABE.
- Fei, S., N. Kong, J. Stringer, and D. Bowker (2008). "Invasion pattern of exotic plants in forest ecosystems." In: Invasive Plants and Forest Ecosystems, Kohli, R., S. Jose, H. Singh, and D. Batish eds. CRC Press, New York, USA.